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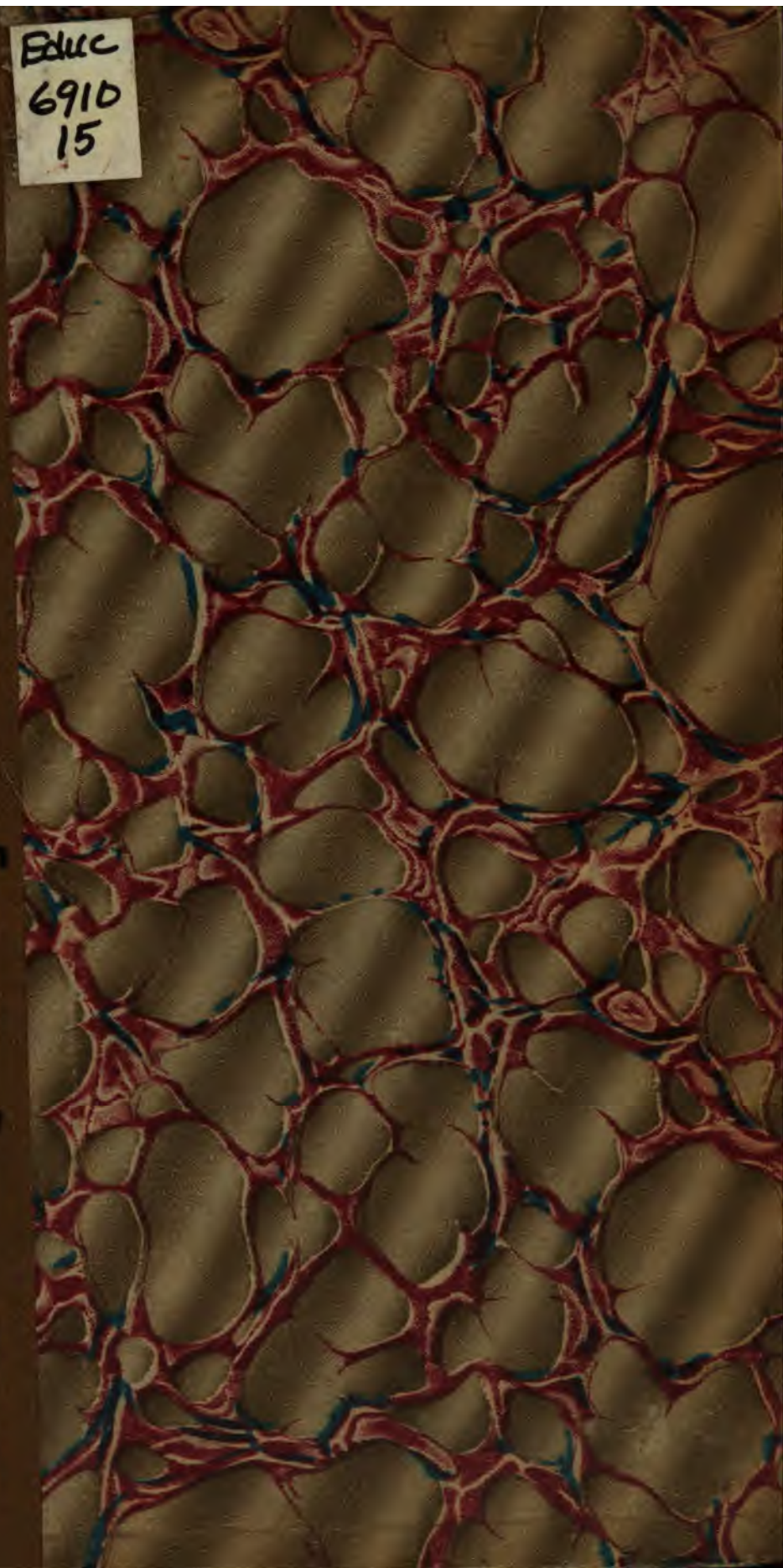
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ENGINEERING  
PRACTICE AND EDUCATION

BY

GAETANO LANZA,

Professor of Theoretical and Applied Mechanics, Massachusetts Institute  
of Technology, Boston, Mass.

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(Reprinted from the JOURNAL OF THE FRANKLIN INSTITUTE, May 1894, to  
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# ENGINEERING PRACTICE AND EDUCATION

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A course of six lectures prepared for delivery in the Lowell Institute;  
three of which were not given on account of the sickness  
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## ENGINEERING PRACTICE AND EDUCATION.\*

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If any one among my hearers expects me to begin this lecture by giving a definition of the words *Engineering* and *Engineer*, I am afraid he will be disappointed. Definitions are attempts to describe, or to give the distinguishing characteristics of the thing defined, in a very few words. To give them is comparatively easy when the things defined are of limited scope; but the more extended the scope, the more difficult does it become to circumscribe them within the bounds of a definition.

Indeed, the term *Engineering* has been used with different significations at different times, and what has been its accepted meaning at any one time has depended upon the particular condition of the world's industrial progress at that period.

Without going into a great many details, I may say that the definition of the profession of the *Civil Engineer*, adopted by the Council of the British Institution of Civil Engineers, in 1828, was, "the art of directing the great sources of power in Nature for the use and convenience of man." Such a definition as this is not only vague, but, if taken literally, it would include a range of work far more extensive than that which has ever been or is now understood as the province of the engineer. Nevertheless, the converse is true of the engineer (omitting the limiting term civil), *i. e.*, the engineer must, in the practice of his profession, direct the great sources of power in Nature for the use and convenience of man.

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\* A series of six lectures prepared for delivery in the Lowell Institute, in Boston, Mass.; the last three of which were not given on account of the sickness of the Author.

At one time, when the science of engineering was still quite limited in its scope, there were only two designations used, viz.: military engineering and civil engineering, the latter term denoting all engineering which was not military.

Later on, as the science, and hence the scope of engineering, advanced, and as engineers began to devote themselves to special lines of work, there arose a large variety of designations, some of which are: civil engineering (no longer used in the original sense), mechanical engineering, mining engineering, etc., and it was assumed that these professions were quite distinct from each other. Indeed, this idea seemed to be in accord with the natural drift towards specialization, and in the line of progress. Now, however, that the tendency towards specialization is ever on the increase, and that progress has gone farther, I think that any one who will examine the facts carefully, and in a judicial frame of mind, will be satisfied that while all these different kinds of engineers are applying their art to a specialty, nevertheless, the art is one, and the functions of the engineer comprise one definite, though wide and extensive, range of work.

We will now proceed to consider some examples of the engineering works of the world of different kinds, in such detail as our time will allow; and when we have done this, whether we do or do not attempt to formulate a definition that will describe the functions of the engineer of to-day and of the future, we shall, at any rate, realize and understand better what is the range, what are the kinds, and what is the character of the work which it is the business of the engineer to perform for his fellow-men.

Passing by the pyramids and the works of the Egyptians and of the Eastern nations, it will be worth our while to consider for a short time what was the character of the engineering work of ancient Rome. And, although the development of such work was very different at different periods of the long centuries during which Rome held her sway over the Old World, it will not be necessary for me to trace its various phases, for, inasmuch as the steam engine had not yet been thought of, it was not possible for advances

to be made at such a rapid rate as that with which they are developed in our own times. Moreover, a consideration of the engineering work of ancient Rome gives us a conception of that of the whole civilized world as it then existed ; for Rome carried her civilization and her engineering everywhere in the wake of her victorious arms.

Indeed, it was very largely to this cause that was due the firm grip that she acquired over the nations that she conquered. They found that their conquerors offered them a civilization more attractive than their own, and that Rome really took an interest in developing their countries, making good roads connecting them with herself, and sending her own engineers to aid them in making other roads and local improvements, besides encouraging them to develop their natural resources. The intimate connection into which they were thus brought with her led them to introduce such improvements as they found that the Romans possessed. Hence we find that Roman roads, Roman bridges, Roman aqueducts and Roman sewers spread to all parts of Europe, and to all countries which came under her domination. Then when the days of corruption came and when she no longer chose to keep herself in the rank of the producers of the world, but sought to be fed by others without making any adequate return ; when she no longer took pains to do thorough work, the Roman example of former times, which had already permeated the other countries of the Empire, still exercised its influence ; and hence it is that some of the most lasting and best examples of Roman works were to be found in Gaul, in Spain and in Africa.

When we stop to consider how they managed to accomplish works of such magnitude and of such merit as they did with the small amount of facilities that they possessed, it seems truly wonderful. Imagine for a moment what would be the aspect of the world, and what the material welfare of our own land, if we were to annihilate the use of steam and of all the machinery that depends on steam engines to operate it.

And yet the Romans handled and transported enormous

weights, which would even make us stop to consider how best to handle them.

When they had to carry some of their enormous monoliths long distances over land, they encased them in cylindrical wooden boxes, and rolled these boxes along the ground, drawing them by means of a very large number of horses; then, for lifting them, the means they possessed were tackle, rollers, screws and wedges.

Their stone-cutting had to be performed by manual labor, the use of fire and vinegar being only applicable to certain kinds of stone, and even then being hardly ever employed, and no other blasting compounds being known at that time. On their roads, however, were often to be found large numbers of tunnels cut wholly or partially through solid rock; some of their tunnels were of great length, as, for instance, the two tunnels at Posilipo, and also the emissary of Lake Fucino, the latter being a wonderful piece of engineering considering the facilities that they could command, notwithstanding its failure to accomplish its object. Moreover, they often went so far as to dress the stone on the sides of their tunnels.

The Roman roads I shall not stop to describe, further than to say that, while, from our point of view, they were decidedly narrow, they were built with an amount of solidity that is surprising, and an amount of labor was expended upon them which is very creditable to their makers; moreover, the number and extent of these roads connecting all parts of the Empire with Rome was something enormous for those days.

While they knew and used most of the metals on a small scale, the principal materials employed in their engineering work were stone, bricks and cement, though some of their bridges were built of wood; and of course works of an intentionally temporary character were often constructed of timber.

On account of the difficulties of transportation the materials for building were obtained as near the place where they were to be used as possible; hence, when available, stone was derived from local sources, and this led to the

establishment of quarries at a great many places all over the Empire, the quarrying being performed, however, by manual labor, with a very occasional use of fire and vinegar. For their larger works, their bricks were well burned; but the cost of fuel frequently led them to build houses of bricks dried in the sun. Next, as to cement: whenever they could find suitable materials near by, they used them, otherwise they secured it from further off. They had at Pozzuoli, near Naples, however, the source of supply whence they obtained their famous puzzolana, and this was sent wherever needed, being transported by water to the nearest point accessible by that means, and thence by land.

The Roman bridges and viaducts were either of wood or stone. In the case of the latter the full centre arch was almost exclusively used. When they could locate the foundations of their stone bridges on dry land, they built good and solid structures; but when they had to lay their foundations under water, they always had difficulty, and these were generally washed away in a short time, notwithstanding the variety of expedients to which they had recourse. Hence we find that there were but few Roman bridges across wide streams, where foundations in the river were necessary, but they had no difficulty in crossing deep and narrow gorges where they could establish solid foundations for their work. They had no means of working under water, or of laying foundations under a considerable depth of water, and when they tried they did not succeed to make them sufficiently secure. Their aqueducts and sewers were fine specimens of engineering, considering the facilities they possessed. The water supply from different sources was kept separate, the purest being used for drinking. Their aqueducts were generally made of masonry or concrete, lined with a mixture of cement and brickdust polished smooth.

They carried these aqueducts across gorges or valleys, on stone bridges or viaducts, sometimes built of two or three rows of arches, one above the other, and this method they preferred to the use of siphons, though they had recourse to siphons at times, and, at times they employed a combination of the two methods. They also used settling

tanks to clarify the water by allowing the impurities to deposit. Besides masonry conduits, they used lead pipes, but they had no pipes that could bear a very heavy pressure. They had no means of pumping, and hence the water had to be brought to the place where it was to be used by gravity. The sewers were, of course, a necessary consequence of the water supply, and these ran at one time under every street in Rome; but after the reconstruction of the streets by Nero, the lines of the streets did not always follow the lines of the sewers, and hence sewers often passed under the houses. The earlier sewers were constructed of cut stone, and so solidly were they built that the Cloaca Maxima can still be seen to-day, although the greater part of it is filled up with earth. The pitch of the sewers was small, however, and hence they were easily choked up. Moreover, a great many cities in different parts of the Empire were provided with systems of water supply and drainage.

Taking up next the ports and the waterways, we find that, their boats being small, the works that they needed, and that they therefore executed, would not look large from our modern point of view; but, considering the times, some of them were magnificent pieces of engineering.

As to ports, when they could they built them in a river, erecting quays of stone or wood. They took advantage of the shelter afforded by natural features, and built protecting breakwaters when they needed them.

When they could reach dry land to build upon they always did so, but when not, they sunk large stones, or cradles filled with masonry, locating them by means of divers, or else they built dikes, and ran in liquid concrete, which, on solidifying, formed, as it were, a solid rock.

They had a great many ports all along the Mediterranean. They had, however, no efficient system of dredging, and their ports were always silting up.

Of course, their navigable rivers formed the natural commercial highways, as indeed they did everywhere before the introduction of railroads; hence, they carried out such improvements as they could, and such as were needed at the

time, by removing obstructions from the river beds and by building sea walls.

They also built a large number of canals, some to connect two navigable rivers, some to connect a river with the sea, when the character of its mouth was such as to render it difficult for boats to enter in rough weather, and also to drain regions that were liable to be flooded in times of freshets. Apparently they were familiar with the use of sluice-gates, but not with the use of locks. Notwithstanding the fact that they had no efficient system of dredging, the canal built by Claudius and Trajan to connect the Tiber with the sea still forms the present northern branch of the Tiber's delta, although all the works long ago silted up; moreover, it served to provision Rome for four or five centuries. Similar canals were built in the case of a large number of other rivers emptying into the Mediterranean and the Adriatic. Other memorable canals constructed by the ancients were the various ones built from time to time to connect the Nile with the Red Sea, and the one connecting the port of Alexandria with the Nile, which was planned by Alexander and executed by Ptolemy.

The Romans operated mines, not only in Italy, but also in various portions of the Empire. In Italy itself it is on record that there were gold mines in the valley of the Aosta, that there was galena in Tuscany, iron in Noricum, and that the Etruscans worked iron in Umbria and Brutium. Elba contained iron mines, and does now; and Sardinia, lead mines. A knowledge of mining, however, preceded the times of the Roman conquests, and mining operations were already under way in the conquered countries before the supremacy of Rome, but the Roman sway developed a greater activity in them.

Both Gaul and Spain were rich in mineral resources. The Romans, and also the Greeks, learned the metallurgical processes from the Egyptians and the races of the East. The Romans used gold in its native state, and hence it often contained silver, copper, or even iron. The enormous quantity of copper used by them would seem to indicate that they found native copper, or else carbonate of copper.

Throughout France we find traces of old Roman iron works, in piles of slag and cinder, these works being at the mines, in consequence of the difficulties of transportation.

Their condition in regard to manufactures, especially in the earlier days, was so primitive as to be hardly worth speaking of.

Such is a very brief and cursory view of the state of engineering practice among the Romans. While we look with the profoundest respect and admiration at the works which they accomplished with the small means at their command, and while those who executed them deserve the highest meed of praise and all the honor that we can give them, nevertheless I would say to the pessimist who thinks that the world is always going from bad to worse, go and try living with such conveniences as were available in the old Roman times, the narrow streets, the uncomfortable houses, the lack of facilities for travelling, the great lack of conveniences as compared with what we possess to-day, and then see whether you will not appreciate the great boon that all our modern civilization and industrial progress has conferred upon us.

They possessed nearly all the materials of Nature that we possess, but they had acquired very little control indeed over the great sources of power in Nature, and before they could make much further progress in their engineering work, they needed to be able to direct these for the use and convenience of man. This was what they specially lacked.

With the exception of the wind as used in sailing vessels, they may be said to have used muscular power of men or of animals for the accomplishment of all their work, and their history is a grand example of what man has been able to accomplish by the aid of little else in the way of power than muscular energy; but when they wanted to accomplish a very large task, they had to use a very large amount of this power; thus, in excavating the tunnel under Lake Fucino, it is said that 30,000 workmen were employed for eleven years.

In order to be able to make advances in material prosperity, and to surround himself with a larger supply of

comforts and conveniences, man needed something more than muscular energy to aid him in his work. He needed to make the wind, the water, but more especially steam, his servants, and to secure the additional advantages of industrial progress which could never have been realized had it not been for the introduction of the steam engine, before he could pass from such works as those of the Romans to the magnificent engineering achievements of modern times. Indeed, we have in this old Roman work a very good example of what engineering science and enterprise was able to accomplish with practically no aid from machinery; and were I to trace, step by step, the progress of the world only in the kinds of work mentioned, viz., roads, bridges, ports, waterways, water supply and drainage, you would be forced to the conclusion that it was by the introduction of machinery, and of steam power to move that machinery, that every point of vantage was gained, and every advance was rendered possible. By way of illustration, we may note that two of the greatest difficulties which the Romans encountered were due to not having the means of establishing secure foundations under water, and not having any such means of dredging as we have to-day. I shall not undertake, however, to trace the decadence of engineering practice through the dark ages, nor its subsequent rise, and the gradual steps through which it has reached its present condition, but shall pass at once to a study of engineering practice as it is to-day, and shall try, by means of a sufficient number of examples, covering, as far as may be, the different kinds of engineering work of modern times, to make plain what is the range and what are the characteristics of the work of the engineer to-day.

Probably the thought of engineering in the popular mind has been associated with what are often called Public Works more than with anything else; and especially with the means of transportation of passengers and freight, and hence with the means of facilitating, and, indeed, of rendering possible the commerce of the world, and also with water supply and drainage. These have often been classed as, and have often been, public works; although the fact is

that works which have been carried on by the government at one time and in one country have been performed by private enterprise at another time and in another country. Moreover, at the present day the aggregate amount of engineering work demanded by private enterprise is much larger than that required by public works; but there was a time when the reverse was the case, partly because manufacturing and even mining, etc., were in their infancy, and were carried on on so small a scale that there was comparatively little opportunity for the exercise of engineering skill, whereas, public works were executed on a very extensive scale; and partly because, in the case of the old monarchical and despotic governments, it was only the government that was rich enough to carry out large works.

For present purposes, then, we will use the following classification of public works: roads, rail-roads, bridges, canals, improvements of rivers and of estuaries, lighthouses, water supply, drainage, irrigation. It is not my object to enumerate and describe the great works in these different lines, but merely to make use of a few as illustrations of the character of some of the work of the engineer.

#### ROADS.

I ought not to pass this subject by without comment, especially in view of the fact that so much general interest is now being awakened in Massachusetts towards having better highways, and I do not doubt that the result of the movement will be that we shall eventually secure them. The very cause that led to the movement, and the movement itself, are added evidences that such work, if it is to be properly done, must be taken in hand by the engineer; and that we shall never have good roads as long as we leave the decision to each man who lives, or each town that is situated on the road, for this means leaving it to men who do not know what are the different methods of making roads, and what are the results that have followed the adoption of any one under certain conditions,—to men, in short, who do not know the experience of the past in that particular line. As to the engineering problems involved in

building, maintaining and repairing a road, I shall only say a few words. In building a road there is always a certain amount of cutting and filling that has to be done; then there may be a variety of engineering problems involved according to circumstances. We may have to cut tunnels or half-tunnels in the side of a cliff, though we try to avoid this when we can. Then, if our road runs along the side of a hill or of a mountain, we may have to build stone walls for considerable distances to support the road on the lower side or to protect it on the upper side, and in these cases it is all-important to see that such walls are built properly, and have a secure foundation. We may also have to arrange such works as will carry off the water of any streams that flow down the side of the hill, and to see to it that these works are able to carry off all the water that will come at the time of freshets, so that the road may not be inundated. Along the Alpine roads we find a great many tunnels cut through the cliffs, and while the water that flows down the mountain side often passes downwards through a channel under the road, it sometimes passes over the cliff.

Probably the most important item to be attended to is thorough drainage, and whatever is necessary to secure it should, of course, be done; and the engineer should so construct it that neither the surface nor the subsoil shall retain water. The surface should not have any hollows which will retain water, and should have a slight pitch towards the drains. The engineer must then determine upon the kind of drains—whether they shall be open gutters, or closed conduits, or blind drains, according to circumstances; but whatever they are, they must be of sufficient capacity, and they must be kept open, and not allowed to become choked up; he must also determine where the drains shall deliver the water, and, of course, he must build whatever conduits are necessary. Next comes the construction of the road itself, whether it is to be a paved street or a macadamized road, and, if the first, what kind of paving shall be used; if it is to be macadamized, whether it shall have a paving beneath the metalling. His decision will be influenced by the nature of the subsoil, as well as other circumstances.

He has then to consider the strength and the wearing qualities of the materials that he is to use for paving or metalling. Then also the proper building of the road, including the consolidation of the material by means of the road roller. Then come the questions of what are the repairs that must be made in order to maintain the road in good condition. A great many other matters are liable to require attention, as the curbstones, the catch-basins, the sidewalks, etc. The engineer may have to erect road bridges, and these, of course, involve all the usual problems of designing and erecting bridges, including the proper foundations, etc., but I shall not stop to discuss these at present.

As to the amount of machinery that will be required, this depends upon the nature of the road. In some cases but little is needed, and in other cases a very considerable amount.

#### RAILROADS.

Let us consider next the engineering work required on our railroads, of which there are about 170,000 miles in the United States, and which exert so large an influence upon the comfort and happiness of all the inhabitants of our country.

I shall not weary you with the story of George Stephenson's efforts, trials and triumphs when he built the famous *Rocket* for the Liverpool and Manchester Railroad in 1829, a story with which every schoolboy is familiar, but shall proceed to a consideration of what is some of the engineering work that has to be done in building, in equipping and in running a railroad.

We may adopt the following as a convenient classification of the different departments that involve engineering operations, viz.: (1) permanent way; (2) rolling stock; (3) stations; (4) signals; (5) bridges.

*Permanent Way.*—Beginning with the permanent way, there is first the location of the road, and this involves a very large number of questions that require careful judgment for their solution; of course, it is necessary to take into account primarily the amount of traffic that can be

secured by any proposed route; at the same time due regard must be had to the expenses that will have to be incurred, both for first cost and also for operating the line; this, of course, introduces a consideration of the grades that will have to be surmounted, the curves that will have to be tolerated, the bridges that will have to be built, the excavations that will have to be made, the difficulties that are liable to present themselves in keeping the road in repair, sometimes the difficulties to be met with to keep it clear of snow, and a host of other considerations; then the actual work to be done in making the surveys, and fixing the location in a new country may involve a good deal of work, and a rather rough-and-tumble life. In America, instead of building the road up to the standard we should desire at the start, it is much more customary to build it poorly at first, and then make improvements as fast as money is earned with which to make them. So, in the first building of the road, the engineer may, to save expense, allow steeper grades and sharper curves than would perhaps be necessary if a little more expense were incurred, with the idea that after the line has been in operation for a while, and has earned a sufficient amount of money to warrant it, the curves can be straightened out and the grades reduced; but he must see beforehand how this can be done. Leaving to one side for the present the matter of the bridges, we will assume that the road is located, and the permanent way is to be built. We have now, to a certain extent, a set of questions similar to those that arise in the case of common roads. There will be, of course, a great deal of cutting and filling. For taking out heavy cuttings we use steam shovels, one of which can do the work of 500 men, and when the embankment is made from earth thrown up from ditches on each side, ditching machines are used, some of which can throw up 3,000 cubic yards per day. In this case, just as in the case of a common road, we must see to it that the roadbed is thoroughly drained, and now, after the roadbed is made, we must put on a good layer of ballast of broken stone. This is the best, for it does not hold moisture. Moreover, that the ballast should be hard and well packed and should not

hold moisture, are considerations of prime importance. On top of this ballast are placed the sleepers, which are carefully laid at the proper distance apart, and are so adjusted as to have an even bearing on the ballast; then their upper surfaces are dressed and the rails are laid down; then the roadbed is covered with gravel, which should be up to the tops of the sleepers, and then the chairs are placed and the rails are spiked down. Then the upper ballast or gravel is tamped in under the sleepers so as to cause them to have so thorough a bearing that they will receive the pressure of the rail equally. Now, besides the bridges on the road, there are a good many culverts, or small bridges that have to be built, where water drains off, and for other reasons. When they are to be permanent they are usually built of stone, but very often temporary ones are built of trestle work, and this is often supported on piles. Hence, we have use, so far, for steam shovels, ditching machines, pile drivers, and sometimes steam dredgers. Next, as to the rails; their weight has gradually increased from thirty-five pounds in the days of George Stephenson, to eighty, ninety and even 100 pounds per yard at the present day. Moreover, while the first rails used were of wood, those of George Stephenson were of wrought iron, but now they are almost exclusively made of Bessemer or open-hearth steel; and this increase in the weight and the strength of the rails has been brought about of necessity in consequence of the increase in the weights of the locomotives from five or six tons for engines like the Rocket to fifty tons and more to-day. Another matter which the builder of a road in a settled country is liable to have to consider is the works needed to avoid grade crossings. Then in regard to tunnels, the American locomotive is so constructed that it can go around much sharper curves than the English or the European locomotive, and hence we can avoid tunnels much more easily than we otherwise could.

After the permanent way is established it requires constant and careful attention, as a variety of unforeseen accidents are liable to happen. Washouts may carry off bridges or culverts, wooden trestles may rot or take fire, rails may break, chairs may break or get loose, spikes may

come out, landslides may occur in mountainous regions, obstructions may get on the track, collisions or accidents may occur. All these things must be guarded against by a most careful inspection, and when anything is found out of order, it should be repaired at once.

Then another matter that devolves on the inspection and repair gang is the following, viz.: the road, and hence the rail, is liable, through unequal settlement, to acquire an uneven upper surface, this occurring most frequently at the joints, and then not only is the riding made uncomfortable, but also there is more power required to draw the train than would be the case if the surface were even. Hence, it is a matter of importance, from the point of view of economy, to keep the roadbed in first-class condition.

Some roads have a dynamometer car which is primarily a car containing mechanism by which we can obtain a record of the pull on the draw-bar at any given instant, or for any given position of the train on the road. These cars are usually provided with another mechanism, which, whenever the car passes a hollow in the track, throws a little paint on the side of the rail near the place. When a road has one of these dynamometer cars it generally uses it for this purpose, and then the trackmen find the paint and proceed to level up the track at that place. If it does not have a dynamometer car of its own, it often hires some one who has, to make the inspection. All these things require a large force to keep the permanent way in order, and it needs to be inspected constantly in all its parts. When, however, there is a break-down, it is often easier to bring men and material from some distant central depot than to try to get along with such appliances as can be found near by. It may be well to say that on our railroads there have been, and are still to be found, a large number of timber bridges, and that, doubtless, in the earlier days of the country, it would not have been possible for the roads to afford the money to build iron bridges; but that now steel bridges are the rule, and while timber is still used for temporary work, its use for permanent work in the way of railroad bridges is fast dying out.

*Rolling Stock.*—We next come to the rolling stock. As soon as the road becomes of considerable magnitude, the works connected with it have to be very extensive, and require a large amount of engineering work. One might imagine that when once the rolling stock is all purchased, if the road is small and not growing, and if the shops and buildings for the housing and the repair of the rolling stock are all built and equipped and in operation, that the looking after everything to keep it in proper order and repair, and the purchasing of the supplies needed, as coal, oil, etc., while it would involve the exercise of considerable executive ability, need not involve any considerable amount of engineering work; but as any one who carries on such work knows very well, the management of a business where so large an amount of machinery is concerned, necessarily involves a large number of engineering problems.

As examples, shops have to be enlarged or new ones built; new and improved or more powerful machinery has to be introduced, which may involve various rearrangements; alterations in some of the details of the running gear or of some other portions of locomotives or cars; the providing of additional space for receiving coal, and of suitable arrangements and facilities for delivering it where needed; making suitable arrangements for keeping cars at such places as are needed on the road, so as to have them ready when and where they are needed; the establishing the necessary yards with the proper tracks and switches; establishing the necessary stationary boilers, pipes, etc., to heat the cars before starting; then comes the care of and the running of the shops, for any railroad, no matter how small, must have at least a repair shop, and, as in such a repair shop, the road must be prepared to make anew a considerable number of the parts of the locomotives and cars, the question always arises how far to go in manufacturing the parts new, and then how far to go in the matter of building, in whole or in part, new locomotives, and hence will arise all degrees of development in this regard, up to the point where the road manufactures all its own rolling stock,

involving, in that case, a very large amount of engineering work.

Another matter that becomes of importance, as soon as the road is able to afford such a department, is a department of tests. This department usually has charge of tests of all kinds, including, of course, tests of oils and tests of the strength of materials, and any other tests which it may be deemed best for the road to make.

Thus, suppose that the road is considering the advisability of adopting some new kind of locomotive for a certain kind of service, and desires to know whether the change is liable to result in economy, especially in saving coal or not, it may be wise to have a series of comparative or even of absolute tests made to determine either its relative or its actual performance in regard to coal and water consumption. Or suppose the road is considering the advisability of making some change in the details of its locomotives or cars, and wishes to determine the effect of the change, as, for instance, in the brake gear, or in the manner of heating the cars, or in some arrangement for ventilating them, all such matters would come to the test department; besides which, if the road is large, there will be enough chemical tests to keep at least one chemist busy, as tests of oils, of paints and varnishes, chemical tests of the materials used, etc. Then, of course, if new shops are to be built and equipped, there arises a variety of problems, first in regard to the foundations of the buildings, then as to the details of the buildings, their proper strength, heating, ventilation, light and adaptability to their purpose; their arrangement so as to require as little handling of the material as possible; the choice of the machinery to be used; its arrangement; whether there shall be much special machinery, and if so, what; the power plant; what kind of engines will be best to use under the circumstances of the case; how many there shall be, and where located; the laying out of the entire system of driving, including shafts, pulleys and belting or other modes of driving, if they are to be used; the steam boilers to be used; the erection of a suitable boiler house and chimney and its location; the foundry;

the forge shop and its equipment, possibly including heavy steam hammers; the boiler shop, with all the necessary machinery, as plate-shearing, bending and planing machines, punching and drilling machines, hydraulic, steam or compressed air riveters, etc., besides the necessary cranes, etc., for handling the boilers in process of construction, as well as the establishing of suitable cranes or trolleys for handling the materials in all the shops in the best and easiest manner; the carpenter shop; the erecting shop for the locomotives. In the case of a number of large locomotive works, cranes are provided which can lift the entire locomotive and carry it from one part of the shop to another.

Then there is the building of the transfer tables, the building of the cars, with all the necessary appliances of brake pipes, heating pipes, lamps, couplers, seats, etc., the painting and varnishing of the cars and upholstering them, etc.

Then, in the case of very large railroad shops, the road might decide to make and roll its own steel, which would, of course, involve a complete furnace plant and rolling mill.

This course is followed by the London and Northwestern Railroad at Crewe, England, where they have a Bessemer plant with four converters, each of which is capable of turning out five tons of steel at one heat. The pig iron, which they buy elsewhere, is melted in a cupola furnace, and the melted metal is then carried by means of large ladles to the converters, which are vessels that can be turned over on their sides and back to an erect position, as they are mounted on trunnions. The converter is turned on its side, and the melted pig iron is poured from the ladle into the converter. Then a powerful blast is introduced, and the converter is turned back to an upright position, when combustion goes on violently, the oxygen of the air burning out the carbon of the pig iron. When this combustion has gone on for a suitable length of time, usually fifteen or twenty minutes, a determined amount of spiegeleisen, *i. e.*, an iron rich in carbon and in manganese, is mixed with the melted mass; then the con-

verter is turned on its trunnions, and the liquid steel is poured into a ladle, whence it is run into the cast-iron ingot moulds, and is thus formed into ingots.

They also have an open hearth plant, with seven Siemens-Martin furnaces, *i. e.*, five twenty-ton, and two ten-ton furnaces. These are, of course, regenerative furnaces where the gas is made in gas producers situated elsewhere, and is brought to the furnaces through pipes laid under the ground. Then the gas on its passage to the furnace passes through a red-hot checkerwork of firebrick, while the blast is introduced after passing through another red-hot checkerwork; the combustion takes place in the furnace, where are placed the pig, the scrap, and other materials required; and then, as the air and gas meet at a high temperature, combustion occurs and the carbon is burnt out of the melted mass; then the hot gases pass out through two other checkerwork chambers to the chimney, thus heating up these chambers, so that the gas and air can be made to enter through them when the other two have become too cool. They have a rail-making plant of 45,000 tons annual capacity, and also a mill for making tires for locomotives and car wheels; a mill for making plates, and a mill for making merchant bars and other shapes which they may require. The steel from these rolling mills is then carried to the other shops, where it is to be used, on cars drawn by a small locomotive on a narrow gauge railroad which goes to all parts of the works.

It may be well to say a little more about these enormous works at Crewe, where the London and Northwestern Railroad can start from the raw material and make all parts of its locomotives and other machinery, except copper plates and brass tubes. These works not only make locomotives, but also all the signalling apparatus, and the signal cabins themselves, also cranes and other machinery, and even bricks, drain pipes, and also gas, besides which they have their own water works. The total area enclosed by the works is one hundred and sixteen acres, whereas the buildings cover thirty-six acres.

Of course, the shops where the locomotives are manufactured and repaired contain an enormous amount of machin-

ery, and among the rest a considerable amount of special machinery. The steel plant is capable of turning out 5,000 tons of steel a year, and the total number of locomotives that have been made there up to May, 1890, was 3,135.

The greater portion of the parts of the locomotives of a given class which they build there are interchangeable, being made to standard sizes; so that if in an accident almost any one part of an engine is broken, another can be found in stock which will be suitable to put in its place and which will fit at once. There are about 6,500 men employed at these works, where about 2,000 engines a year are repaired, and where as many as 146 have been made in one year.

To establish and keep up this enormous place it has been necessary for the road to make provision for enabling its workmen to live there, as the town has practically been built up by the railroad. The company own about 850 houses, and they have built at their own expense a Mechanics' Institute and a church, and they have done a great deal to furnish to their employes and their families opportunities for improvement and amusement.

The cars are not made at Crewe, but at Wolverton, where the works cover about fifty acres, and where they employ 2,200 workmen, and where they buy the wood in the form of logs, and again they have a narrow gauge railroad running to all parts of the works, and cranes of all sorts, so as to be able to handle the material and the work easily. The timber is sawed into planks or whatever form may be desired here, and then it is put into a drying room and seasoned, before it is used in building cars. The wheels are also made at Wolverton, these being wood wheels with steel tires, the wood being forced into the tires by hydraulic machinery. Then, of course, there is done here all the upholstering, painting, varnishing, etc. When we consider the extent and magnitude of these works, it is evident that there is the necessity for a very large amount of purely engineering work. The putting up of the buildings alone involves questions of adaptation of the arrangement to the greatest economy in handling, consistent with efficient working; adaptation of the form and proportions to the work to

be done in them; questions of suitable foundations; questions of light; questions of strength of materials, especially considering the heavy loads that have to be borne in some of them; questions of chimney power, and of foundations for and stability of chimneys, of draught of chimneys, etc. Then besides this the road has to do all the engineering work for a large town and has to make provisions for a great deal that usually belongs to the town to provide, and not to a railroad corporation, thus it has to supply the town with water and gas, and all this means water works and gas works, and the solution of engineering problems that arise in connection with them.

Then it has not only to build its own shops but also houses in the town, hence it has to make brick.

Then in order to make all the saving possible in labor, there is required a large amount of special machinery, and to design such, a man needs to be familiar with mechanism, and with the design of machinery, including questions as to its strength, its stiffness, and its proportions generally, as for instance, its bearing surfaces, etc.

Then need I say that the steam plant needs attention? Are the engines and boilers, and their arrangement and running such as will ensure the greatest economy? Also the amount of coal and iron and other materials brought into these works must be something enormous, hence means must be provided for receiving them, for unloading them, and for storing them until they are needed.

Then, besides all these questions which involve a knowledge of mechanism, of strength of materials, and of steam engineering, etc., we have use for electricity in various ways. The first to present itself to one's mind in connection with a railroad will naturally be the signalling; but there are also other connections in which, if it is not much used yet, I do not doubt it will be ere long, viz: electric lighting, not only for the shops, but also for the cars, for although electric lighting of steam cars has not thus far progressed to the point where it is at all rivalling or likely to rival for some time the methods of lighting by gas or by oil; nevertheless, I believe that in course of time more

progress will be made in this direction, and then we shall come to have our steam cars lighted by electricity; also in the use of electric brakes, which at present are employed only to a small extent; also in the use of electric cranes, which are the modern form of crane without any question. Indeed, electricity is gradually displacing other methods of driving cranes in our large shops and rolling mills and bridge works. By using it we avoid a great many clumsy methods of transmitting power, for the power has to be applied in such a way that the crane can be driven wherever it stands in its travel. An electric motor carried by the crane itself, with the connecting wires, furnishes an easy and neat method of transmission, and does not involve so much loss by friction. The application of electric motors to cranes will, in my opinion, be extended to a large extent to other machinery in our large machine shops and manufactories, and I believe it will not be many years before electric transmission of power will displace a great deal of the shafting and belting with which our shops are so much filled up at present.

Besides all this we have opportunities and the necessity for a large amount of engineering knowledge and engineering work in the design and construction of the locomotive itself.

What are the conditions which we wish our locomotives to fulfill? They are to draw our trains at as high a speed as is consistent with safety, and to do this with the least expenditure for coal, for water, for repairs, etc., also to fulfill all the special conditions of the particular service which they are to perform, such as going around sharp curves, going up steep grades, hauling heavy trains, etc.

Of course, it is necessary that they should have the requisite strength and stiffness. Now, we have here at once questions of mechanism, questions of strength of materials, and questions of steam engine economy.

In the infancy of any new industry questions of the proper strength of the machinery, and of adopting such arrangements as shall insure economical operation, are very likely to be neglected; the main efforts of the promoters

being generally directed towards making the machines work at all; and if economy is lacking, the only result is that the prices of the products are put at such a figure as to cover the expenses and provide a good profit. Then there is a strong tendency, as long as the companies can make money as fast as they desire, without attending to matters of economy, to disregard them; and if they make any attempts to increase their income, it is rather by an increase of the plant than by introducing more economical working into what they already have. Hence it is that in the early stages of an industry, there is usually less engineering and less scientific work done than later, for scientific work is precisely what is needed to produce economy. But after the industry has been carried on for a long time by a number of people, and competition has become rife, then those who are at the head of it find themselves forced to consider questions that affect the economical working of their industry, for on the proper solution of these questions depends success or failure. It follows, therefore, that in an industrial country like our own, there is more and more demand for scientific work, and, hence, more and more demand for engineering work. I might cite a great many cases to illustrate this matter, but one of the most marked, perhaps, is that of making illuminating gas, where it has been the fact until very recently that so much money could be made anyway, that the gas manufacturers did not care to take pains to avoid waste, and very little, if any, effort was made to economize, and hardly any attempt to operate the works on sound engineering principles.

But I am digressing from my subject. Coming back then to the locomotive, let us see how the remarks I have been making apply to that. In introducing the locomotive into American practice, it became at once evident that the rigidity with which locomotives were being built in Europe was not suited for travel on roads such as we could afford to build at the time, nor for those containing as sharp curves as it was, and still is, frequently desirable to make. Hence, to the credit of American genius be it said that our railroad men at once proceeded to introduce the modifications

necessary to render the locomotive a more flexible machine, which would stay on the track, even if the latter were uneven, and if the curves were sharp and which should be so easily accessible in all its parts and so simple in construction that it could be easily repaired. Moreover, the modifications introduced by American inventive genius, were good features, even after the country developed so that we could have better permanent way, and some of these points are of such decided advantage that we find more and more tendency to imitate them, on the part of our neighbors across the ocean, in their most modern constructions.

Now, these efforts might be said to have been attempts to make the machine work at all, and there was too much tendency to determine the question of strength of the parts by what was and is sometimes called practical experience, *i. e.*, by waiting till something broke before pronouncing it too weak, and then making it larger, *i. e.*, putting in more iron in subsequent constructions.

To illustrate the fallacy of such a course by a very extreme case, I may say that, in the early days of locomotive practice, parallel rods were sometimes made of circular section, and that as soon as the speeds became at all considerable, such rods were almost sure to break. Now, suppose the course outlined above were followed and a larger rod of circular section substituted in subsequent constructions. Any one at all familiar with the scientific principles at the foundation of the theory of the way in which a beam resists a transverse load, could easily predict the result, which is that the new one would be practically no stronger than the old one, while weighing more; for, as soon as the speed of the locomotive is at all considerable, the transverse load, due to the action of centrifugal force on the parallel rod, forms by far the greater part of the load that it has to sustain, and by the course adopted this load would have been increased in the same proportion as the power of resistance of the rod. A little figuring in such cases would save a great deal of costly experience, and often a number of accidents. Of course, railroad men know better now than to use round parallel rods, but there is not

care enough taken yet in calculating the strength and stiffness of all the different parts of locomotives.

Turning, now, from questions that involve the strength of materials to those that involve economy, we find that fuel, both wood and coal, has been so easily and so cheaply obtained heretofore that railroad men paid little or no attention to this matter; and while I do not believe that the locomotive is as wasteful of fuel as is frequently imagined, nevertheless, hardly any really serious efforts were formerly made to ascertain and develop means for reducing the coal consumption, such as have been made constantly in the case of large stationary and marine engines, and it is a fact that the man who would run a stationary or a marine engine of like power, with as large a coal consumption as is used in the case of the locomotive, would be deemed a very wasteful man and unfit for his business. Of course, the peculiar duties of a locomotive, and the special conditions under which it has to work, may not, and probably will not, enable us to realize as great economy as we do in the other cases, but it is certain that a little earnest, scientifically conducted work would enable us to realize more economy than we do, and how much more we cannot predict until more attempts have been made in a thoroughly scientific manner.

Even where tests have been made, we find a laxity allowed in them which would not be tolerated in making tests of a marine or stationary engine. As an example, I have frequently looked over the results of some locomotive test, hoping to gain some information from it, and when I came to examine the way in which the test was made, found that the conditions were such as would render it entirely untrustworthy if it had been made on a stationary or a marine engine, and I cannot see how the fact that it is a locomotive makes the test where there is so much looseness any more trustworthy. To cite the various improper things that are done in this regard would take too much time, and I will only mention one which has been done altogether too often, viz.: applying the steam engine indicator to one cylinder alone, and guessing that the per-

formance of the other is like unto it. The chances of reaching the truth are not much, if any, greater than if the whole estimate had been made by guessing, and this latter course would have saved work. But we are coming to the time when our railroads can no longer afford to disregard questions of economy of fuel; and these matters are, slowly it is true, but surely, coming into prominence.

One evidence of the state of affairs to which I refer is the remarkable indifference that existed only a few years ago in regard to the introduction of the compound locomotive. It had at that time already been introduced into Europe for several years, and although it had not really gone very far beyond the experimental stage, it had, nevertheless, been so far developed that it had been experimentally proved without question that a decided saving of coal could be effected by its use. Nevertheless, I listened to discussions among railroad men held at that time where very little interest was shown in furthering its introduction here, and where I heard grave doubts expressed as to whether it would be wise to introduce it into America, and when they attempted to give their reasons for these doubts, they would raise all sorts of objections as to very minor points which it would be very easy to adjust to our needs by the exercise of a very little American ingenuity and adaptability. The compound locomotive, however, came to America, and came to stay; and so prompt have Americans been to adopt it, that we now manufacture a great many in this country.

Of course, those that we have made are decidedly American and not copies of European styles, and most all of our large locomotive works now build more or less of them; and naturally we have a number of different styles, inasmuch as they have been planned and worked out by different men.

But now, if we are going to imagine that there is gain in the simple fact of compounding without regard to how it is to be done, what proportions of cylinders should be employed and what other arrangements should be used, we shall not realize the economy that we might, and we may even fail to realize any; since it will be per-

factly possible for a well-proportioned and well-made single locomotive to be more economical than a badly made compound one. If, on the other hand, the introduction of the compound locomotive is to mark the beginning of an era when the same criteria of accuracy and reliability shall be applied to determine the value of a locomotive test as are applied in the case of stationary and marine engines, where we demand and perform more or less experimental work with scientific accuracy; and if the same sort of work shall be demanded and performed in the case of the locomotive, then the benefits conferred by the introduction of the compound locomotive will not be confined to the cases where it is used, but will also react in bringing into being a more economical class of single locomotives, while it will also cause us to adopt in the design of compounds such features as will be conducive to the greatest economy of coal.

I suppose that after having said so much about compound locomotives, I ought to say a few words by way of explaining what is a compound locomotive, and what is the reason why we are justified in expecting any greater economy with it than with a single locomotive.

In the single locomotive there is one steam cylinder on each side near the forward end, and the steam from the boiler enters each of these cylinders, and causes the respective pistons to move. Before the motion of the piston in either cylinder is completed, however, the steam supply is cut off, and the piston is caused to complete its stroke by the expansive force of the steam. Then during the return stroke the steam on this side of the piston escapes into the exhaust, while that which enters on the other side of the piston is pushing the piston the other way and doing the work.

Thus, in the single engine, the steam enters the cylinder, is cut off at a certain fraction of the stroke, expands, and then escapes directly into the air; and this series of actions is carried on in each cylinder independently of the other, there being really two separate engines connected to the same shaft with the cranks at right angles to each other.

Now, in the compound locomotive, the steam, when it comes from the boiler, enters one cylinder called the high-pressure cylinder, but, when it has expanded in this cylinder, it does not escape into the air, but into another and larger cylinder, where it expands again, and acts upon another piston by its expansive force, and then, from this cylinder, it escapes into the air.

Again, there are a variety of such arrangements that can be made; thus, we may have one high-pressure and one low-pressure cylinder on each side of the locomotive, *i. e.*, one compound engine on each side, making a pair of compound engines. This arrangement is called a four-cylinder compound. Another arrangement is made by having only two cylinders for the whole locomotive, the high-pressure cylinder on one side and the low-pressure (a larger) cylinder on the other side. A third arrangement is by having one compound engine on each side of the locomotive, the high pressure being inside of the low pressure, the latter being annular and having an annular piston. Then still another method, which is English, is to have two high-pressure cylinders, one on each side of the locomotive and one large low-pressure cylinder underneath, in the middle.

Now, these different arrangements are made by different builders, and each one claims advantages for his own. As to which is best, when the proportions are correctly adjusted, only careful and accurate experiment can determine. As to the reason why we should expect any gain by compounding, it is merely because the difference of temperature of the walls of the cylinder, when the steam enters and leaves it, is less, and hence cylinder condensation should be less, in a good compound than in a single engine, since the expansion is all completed in one cylinder in the latter, whereas it only completes its expansion in two cylinders in the former.

Besides this, there are a great many questions of interest and of importance to be made the subject of careful investigation, in connection with railroads and locomotives. I cannot pretend to give a list, but will mention a very few, as follows: The law of variation of train resistance,

or the force necessary to draw the train at different speeds ; the air-brakes, about which a number of questions should be investigated ; heating, ventilating and lighting cars, etc. Thus, heating of passenger cars by steam from the locomotive has come to stay, and has become so much of an accomplished fact, that it has been adopted on a large number of roads, and will have to be on all ; but there are a great many different possible ways of accomplishing it just as there are many ways of heating a building, and there has hardly any progress been made as yet in regard to ventilating passenger cars.

But I think I have said enough to give you an idea of what a multiplicity of engineering questions arise, and what an amount of engineering work and opportunity for investigation there is about a railroad.

*Bridges.*—The greater number of our largest bridges are built to form a portion of a railroad, for, in this case, heavier loads are to be supported than when they form a part of a highway. The Brooklyn suspension bridge, which possesses the second longest span in the world, is no exception, for it carries a cable railroad. Their construction is sometimes undertaken as that of public works, as, for instance, by the city or town, and at other times it is carried on by private enterprise. The city, the railroad company, or other corporation, may impose on its own engineer the task of producing the entire plans, both the foundations and the superstructure ; or it may delegate the making of these plans to another engineer or to some bridge-building firm ; or, on the other hand, in the case of the latter, it may be only the superstructure which is entrusted to the firm to construct, while the foundations are kept as a separate undertaking to be built by the road itself beforehand. When an engineer has to plan a large bridge, it often happens that the foundation is by far the most difficult part of the work. Thus, at the places where the foundation is to be established there may be clay or hard sand, and, on the other hand, there may be quicksand or mud. He may have to build the foundations on piles, if it is not too large a bridge, or he may have to excavate, sometimes to a great depth, before he reaches something that is suitable for a foundation.

Then, again, he may have to establish his foundation under water, and here he may be called upon to perform a great deal of excavation. If it is to be far under water, he may have to resort to pneumatic caissons; and now by the use of machinery we are finding the means of establishing foundations under water at a depth too great to permit of the use of pneumatic caissons. In any of these cases there is a large amount of engineering involved in planning the work, and also in executing it. A thorough examination of the ground has to be made, including the taking of borings to ascertain how deep the excavation will have to be before something is found which is suitable for a foundation, and the nature of that something. Then the plans have to be made and all necessary calculations to determine what should be constructed, and how it should be built.

Next comes the building of the foundations, and this may involve a large amount of engineering work, especially if pneumatic caissons have to be used, and if part of the work is to be built under water, as the whole erection will involve the introduction of a large amount of machinery, including the use of compressed air, cranes which have to be operated by some kind of power, hoists, etc., and the greatest care will have to be exercised in sinking and locating the caissons, and in preventing them from getting out of place while the excavations are in progress, and in preventing accidents. Then, when the excavation is made, the whole must be adjusted and all must be properly filled up with concrete, and then the masonry can be built above. Of course, this sort of work with difficult foundations is not the every-day work of the engineer in general, but all varieties of foundations are met with where the piers cannot be built directly on the ground, and where we must either build on piles or must have recourse to coffer-dams, and thus be able to excavate the earth until we reach a suitable foundation, or where some sort of crib has to be built, which shall confine a certain amount of loose and flowing sand, and thus render it suitable to build upon. Moreover, the matter of securing a good foundation is an all-important prerequisite for building a bridge that is to stand. Other-

wise our bridges would share the fate of those of the old Romans.

Then comes the designing of the bridge, in such a way that it shall have sufficient strength in all its parts to resist the stresses coming on those parts. Moreover, in this work care must be taken to figure every detail, and nothing must be disregarded, for if one of the minor details be neglected in the calculation, this neglect may lead to disaster. It is very common now, however, for a railroad company to build, or have built under its own direction, the masonry foundations for all the bridges on its road, to *erect* all of them itself, but to have them built, and sometimes also designed, by some bridge-building firm. Now, when the designer, whether he belong to the railroad or to the bridge works has made the design, and has worked out the stresses in all parts of the structure, including all the details, pins, rivets, fastenings, hangers, anchors, etc., and has also made the detail drawings of the bridge, these drawings, or rather the blue prints, can be sent into the shop, and the construction of the bridge can begin.

Making the design, the calculations and the drawings, of course, requires engineering work, and especially an application of the strength of materials, to see that every detail is of the proper strength and stiffness. But I propose to call your attention especially to what engineering work has to be done by the bridge builder in fitting up his shop to do this kind of work properly; and this will be made most evident by a consideration of the engineering problems which one who carries on a bridge works has to solve, and the engineering work he has to execute.

Of course, the method of carrying on the manufacture of bridges, and the amount and character of the engineering work involved, will depend upon the magnitude of the works, which may be small or large, and which may be built for the purpose of merely manufacturing the bridges from iron or steel which they buy, or which may be attached to, or form part of, an iron or steel works.

If they are very large and are connected with an iron and steel works, they may begin with the ore, and make their

own pig iron, then transfer it to the Bessemer converters, or to the open hearth furnaces and make the ingot steel, or to the puddling furnaces and make wrought iron. Then the product is rolled, or squeezed, or hammered into blooms, and then these are cut into suitable lengths, and after being heated again, are rolled into angle irons, channel bars, T-irons, Z-bars, plates, etc.

By way of illustration, we will consider the following brief outline of the method followed at Phoenixville, *i. e.*, at the Phoenix Iron and Steel Company's Works. At one time they used to make their own pig iron, but now they buy it and convert it in their open hearth furnaces into steel.

After having been in the reheating furnace, the ingot goes to the first set of rolls, where it is rolled into blooms, and then to a powerful shears, where it is cut into the lengths needed for different purposes.

In connection with these rolls and shears, which are very heavy, there is some ingenious machinery for performing what may be called the handling of the ingot, *i. e.*, for placing it in the right position on the rollers which feed it into the rolls or shears, for tipping it over when it is desired to do so, etc.

Of course, provision is made in this portion of the works for quick and convenient handling of the heavy ingots, etc., by means of trucks and cranes.

Then from the blooming mill the blooms are placed on trucks, which are drawn by a small locomotive to the rolling mill, where they are heated again, and then rolled into the desired shapes, angles, channel bars, I-beams, etc., and these are then cut off to the proper lengths by saws. In cases where it can be done, the sawing is performed while the steel is hot; but in a number of cases it has to be done when the steel is cold. Then, after leaving the rolls, the beams, channels, angles, etc., are straightened in machines with which the shop is fitted for this purpose. There are also certain machines specially designed to cut the ends in various shapes, such as are needed in fitting different pieces together in the manufacture of a bridge.

The rolling mill is, of course, fitted with a complete sys-

tem of trolleys and other devices for handling the material, for delivering it to the rolls, for receiving it when it has passed through, transferring it to the next place through which it has to pass, etc. When the beams, channels, angles, etc., come from the rolling mill they are ready for the market, or to be used in the manufacture of bridges.

Then, there is the bridge shop, where all the different pieces that are to compose the separate girders and the other parts of the bridge are assembled, and the necessary punching, drilling and riveting is performed.

Of course, this shop must be large enough to admit of whole girders being put together, and also easily handled and worked upon. Here, therefore, there are provided ample floor space, large and powerful travelling cranes to handle very heavy material, and punching machines, drilling machines and riveting machines in very considerable number. Of the latter, some are hydraulic riveting machines, conveniently located for the work they have to perform, but fixed in position; while others are portable riveters, operated by compressed air. Then there are many other machines which I will not stop to enumerate. Then, in the yard is a travelling crane, used to load the separate girders and the other parts of the bridges on to cars.

The works are very extensive, and there are numerous other shops used for various special purposes, but I shall not speak of them, as I am not attempting to give you all the details of the Phoenix Works, but only to illustrate to you what kind of operations have to be carried out and what kind of engineering problems present themselves for solution outside of the design of the bridge.

Now, in such works everything that can be done to save labor in handling, or in any other way, is, of course, so much gain. Hence the absolute necessity for a complete system of trolleys, etc. Then again, since holes for rivets and other purposes have to be located, and other features marked by template, whenever some more expeditious method has not been devised, you will find that the various bridge works endeavor to devise some machine to perform as much of the punching or drilling as possible without using a template.

This becomes of special importance in the case of the long lines of rivet holes that have to be made in the plates and angle irons which are used to form the flanges and webs of plate girders; so, at these bridge works we find a machine devised for this special purpose.

Without going further into detail, it is plain, after a bridge is designed and the drawings are all made, and it is ready to be constructed, that in connection with the works a large amount of engineering work must be performed. Of course, the planning and building of the shops in such a way as to be well adapted to their intended purpose, the selection and arrangement, the devising of suitable machinery, some of which (and sometimes considerable) is special machinery, the arrangement of the power plant, and the entire arrangement of the cranes, trolleys, etc., for handling the material, and for loading the finished structures on to the cars to be carried to their destination, all involves a large amount of engineering; and this does not cease with the establishment of the works, for the same kind of engineering questions are constantly arising—questions of mechanism, questions of strength of materials, questions of steam, etc.

At the New Jersey Iron and Steel Company's works electric cranes are used, and some of the machinery in the bridge shop is driven by electric motors. At Edgemoor, is another bridge works where the entire arrangement has been recently laid out with especial reference to convenience and ease of handling, and also to the use of special machinery, and I will outline briefly some of the methods followed in these works in order to show the sort of planning that was performed.

The material is received by rail in the yard, and is taken off the cars, and placed on little trucks running on narrow gauge tracks, on which it is rolled along and taken into the shop.

There are numerous lines of rails, parallel to one another and leading to different parts of the shop. These rails extend the whole length of the shop in one direction, and hence, the motion of any piece in the lengthwise direc-

tion is accomplished by means of these trucks. When, however, the material is to be moved in a transverse direction, it is carried by chain falls attached to trolleys moving on rails on the ceiling laid in a direction at right angles to the rails on the floor. This system of rails on the floor running in one direction and rails on the ceiling running in a direction at right angles to them is adopted throughout the greater part of the shop; but when the larger pieces have already been formed, they are handled by means of a series of jib-cranes actuated by hydraulic power, in which the jib can be made to rise, and lift the piece, and also to turn around, while the chain falls can be moved lengthwise along the jib.

This method of handling the material is peculiarly adapted to such work, because the pieces that have to be handled are mostly long and narrow.

Next, as to the special machinery in use. The following is the method of making the eye bars from a straight bar. The straight, flat bars of proper size are taken to some small furnaces where the ends are heated; then, when hot, the ends are put flatwise into an upsetting machine actuated by hydraulic pressure, where they are upset, and formed into the proper shape for the head by being squeezed between suitably formed dies. This having been done, the bar is at once carried to a hydraulic punching machine, where the hole for the eye is punched usually before the end of the bar has had time to lose its heat. When the eyes have been punched it is straightened if necessary, and then taken to the boring machine, where there are two tools, by means of which both eyes are bored at once.

Then the eye bars are taken on the trucks to the annealing furnace. Here a number of them are put into the furnace together and annealed.

There is also at these works a multiple punch with a specially designed feeding mechanism for the purpose of punching the holes in the plates, angles, etc., of a plate girder, or of any other construction of this character, as in the case of a bridge column. The remainder of the machinery I shall not refer to.

Of course, there have to be powerful pressure pumps to provide pressure for all the hydraulic machines, of which there are many and powerful ones, such as the upsetting machine, the straightening machine, the punches for the eye bars, the hydraulic jib-cranes, etc.

It is plain that the planning and putting up of such a shop, with proper regard to economy of labor and economy in all parts, involve a large amount of engineering, and of the kind that would usually be called mechanical rather than civil engineering, although the building of bridges has commonly been associated with the latter.

Certain styles and sizes of bridges can be made at the works and shipped to the places where they are to be erected; but when they become very large, they outgrow the capabilities of the bridge works, and a great part of the construction, if not all of it, has to be performed on the ground. In these cases a great deal of engineering work of very varied character is often involved.

Perhaps it will be well to illustrate the character of the work that may have to be done by referring to examples of one or two modern bridges, first making a few general remarks:

(1) While some very large wooden bridges have been built, and while there are still in existence in the United States a great many more bridges built of timber than there ought to be, nevertheless, they are rapidly disappearing, and bridges of any considerable size and importance are no longer made of timber.

(2) Masonry bridges are limited in span.

Hence, the modern bridges of long spans are built of iron or steel; and the necessity is constantly arising to cross greater and greater widths; and, every little while, one is built with a span greater than any that has preceded it. Thus, the famous Britannia tubular bridge, built by Robert Stephenson, in 1850, had two central spans of 459 feet each, and shore spans of 230 feet each, and was thought at the time to be a triumph of engineering. It carried the railroad across the river in rectangular wrought-iron tubes.

To us, to-day, it and others built like it look old-fashioned

and cumbrous. Since then many girder bridges have been built in various parts of the world.

By way of arched iron bridges we have quite a number, but the most noteworthy are the two that were built over the Douro River, at Oporto, Portugal, and the Garabit viaduct, over the Truyère River, in France, all of them having been built by Mr. Eiffel, and having spans of 525, 571 and 541 feet, respectively.

Of suspension bridges I will only mention the Brooklyn bridge, with a span of 1,595 feet, designed by Roebling, and opened in 1883.

At the time this bridge was built, this was the longest span in the world, and it has not yet been outdone by any other suspension bridge; but now we have the Forth bridge with a span, of 1,700 feet; how long it will be before a bridge is built with a longer span is difficult to say.

The central span of the Brooklyn bridge is 1,595 feet in length between the two towers. These towers are built on solid rock, 78 and 45 feet, respectively, below high water, and the tops of the towers are 277 feet above high water. The clear headway at the center is 135 feet. There are four suspension cables,  $15\frac{1}{2}$  inches diameter, each made of 5,282 galvanized steel wires, side by side, without any twist. The width of the bridge is 85 feet. At the center, and 12 feet higher than the rest of the bridge, is a footway  $15\frac{1}{2}$  feet wide; then the passages for teams are on the outside and the cable railroad between the footway and each of the passages for teams.

When it is necessary to span a considerable width, and to leave a considerable clear height underneath the bridge, and when it is either not possible, or not allowable, to build false work underneath, we have to build the bridge out from the supports. Whereas several bridges have been built out from the supports by dint of special contrivances, the two kinds that would seem to be best adapted to it are suspension bridges and cantilever bridges. A cantilever is the name given to a bracket fixed at one end and free at the other, the loads being placed either at the free end of the bracket or anywhere along it. Now, in order to render a

bracket or cantilever able to bear a load, it must be fastened in some way at the fixed end so that it will not tip over, since the other end is free. Also, the cantilever, if loaded at the end, needs to possess a greater resistance the nearer we approach the fixed end, hence it should have a greater depth at the fixed than at the free end. Now, the idea of a cantilever bridge is to have projecting from each of the two supports a bracket or cantilever, these two projecting brackets approaching each other, and covering a large part of the distance to be spanned. Then a plain bridge girder is hung from, and supported by, the two free ends of the two cantilevers, and spans the remainder of the distance.

Now some provision has to be made to keep the cantilevers and their supports from tipping over. This is accomplished by having another bracket extend from each support in the opposite direction, and tying down the free ends of these brackets in some way, as by tying them down to weights of sufficient magnitude resting on the ground, or by any other means that will hold them down.

Hence, we find that cantilever bridges have a bracket, deepest at the supports, extending out each way from the support, the river bracket supporting at its free end one end of the central truss, while the end of the shore bracket is tied down in some way. In cases where it cannot be tied down, as where there are two cantilever spans in succession, of course the two brackets projecting from the middle support in opposite directions are easily balanced as far as dead load is concerned, and then sufficient stability to take care of the moving load must be given by providing a sufficiently large base for the pier or support to rest upon, the moving load bearing, of course, a small proportion to the dead load.

The cantilever bridge over the Niagara River near the Falls, was the first bridge ever erected in the United States, and in the world that deserves the name; although in one sense any continuous girder bridge might be called a cantilever bridge, and although several bridges have been cantilevers during the building, *i. e.*, they have been built out from the supports, such as the Douro bridges, or the St. Louis bridge.

This cantilever bridge over the Niagara was designed by Messrs. Schneider, Field and Hayes. It was contracted for on April 11, 1883, and opened on January 1, 1884. The river span, or distance between the piers, is 470 feet; the distance from each shore abutment to each tower is 195 feet, each tower panel being 25 feet, and each river arm 175 feet, while the central girder is 125 feet long, and the total length, exclusive of the approaches, is 910 feet.

The largest cantilever bridge in the world, and also the one having the largest span, is the Forth bridge. This is a railroad bridge, and crosses the Firth of Forth not far from Edinburgh. The estuary at this place is very much exposed to heavy gales and rough seas, but just here is the island of Inchgarvie, situated about half way across; and this was the only place in the entire width of the stream where an intermediate support could be established. To bridge the distances from Inchgarvie to the north shore, and from Inchgarvie to the south shore, would require very long spans; thus the spans actually adopted in the Forth bridge were 1,700 feet, whereas, in 1873, a company had actually begun the erection of a suspension bridge at this same place, the spans of which were to be 1,600 feet each, but the destruction of the Tay bridge by the wind in 1879 brought about the discontinuance of the work, and the decision was made to erect a cantilever bridge. The plan was approved in 1881, the work was begun in 1883, and the bridge was opened in March, 1890. There are, as has been explained, two river spans; hence, in the bridge proper we find three supports, one on the north shore, one on Inchgarvie, and one on the south shore. Each of these supports or towers has a cantilever projecting from each of its two sides, or, if we call a tower and its two projecting cantilevers a double cantilever, we have, in the bridge proper, three double cantilevers. Then uniting these in the two main spans are the two central girders. Of course, the roadway is very far up above high water, and hence there are long approach viaducts on both the north and the south sides.

The dimensions are as follows: Total length of bridge,

including the approach viaducts, 8,296 feet, or excluding them, 5,330 feet. The central tower on Inchgarvie, 260 feet long; the other two, each 145 feet. Each of the six cantilevers is 680 feet. Each central girder is 350 feet. This makes each clear span in the river about 1,700 feet.

Each of the three towers is supported on four circular granite piers, so placed that the centers of the four form the corners of a rectangle, whose width is in all three cases 120 feet, but whose length is, in the case of the tower on Inchgarvie, 270 feet, and, in the case of each of the others, 155 feet.

The greater length on Inchgarvie was necessary in order to give the middle tower sufficient stability, since it could not be tied down like the other two. On top of these piers rest the towers, each of which consists of four columns well tied together by suitable bracing. These columns approach each other, two and two as they rise, so that their centers at the top form a rectangle only 33 feet wide instead of 120, the length of the rectangle being the same as at the base. Of course, there are skewbacks between the bases of the columns and the piers.

While the materials were brought from elsewhere, practically all the work had to be performed on the ground, hence it was necessary to build and equip very large works. These were situated on the south shore, whereas smaller works had to be established on the north shore and on Inchgarvie, and easy means of communication had to be established between them, and between them and all parts of the work, for freight, for passengers, and also by means of the telephone. Moreover, the works had to be fitted with a very large amount of machinery, a great deal of which was special machinery designed for this particular work, as will be seen later.

The planning, erecting and superintending of these very large works alone involved an enormous amount of engineering of all sorts, the design and purchase of some, and the manufacture of other machinery, the erection of shop buildings suitable for their purpose, the arrangement of the machinery, the selection and arrangement of the various

power plants, the establishment of a complete system of electric lighting, of a complete system of telephonic communication, of complete facilities for travel of the workmen by boat and by rail, and for the carrying of the materials to the points where they were needed, by rail or boat, as well as the establishing of all the machinery for handling the material, as cranes, etc., and of the means of running this machinery; the establishment of suitable means of receiving and distributing the materials, the steel, the fuel, the cement, the sand, etc., the plants for making and distributing compressed air, and a host of other matters, including the erection of a very considerable number of houses for such of the workmen as could not easily find quarters elsewhere. The amount of engineering work required to carry on all this properly is so great that it is difficult to form an adequate conception of its magnitude. In order to aid in the formation of this conception, I will give a few figures illustrating the enormous scale of the operations involved in this work, before I proceed to the further description of the details of the bridge and of the work.

The total amount of steel used in building the bridge proper, *i. e.*, the three double cantilevers and their two central girders, was about 51,000 tons. The total number of rivets used is uncertain, but is considerably in excess of 6,500,000.

There were used, up to November 30, 1889, 64,315 cubic yards of concrete, and 48,356 cubic yards of rubble, and 27,429 cubic yards of cut stone. The provision for carrying materials from the works on the south shore to the places where they were needed consisted of four steam launches, eight large steam barges, and a lot of barges or lighters which were towed by some of these.

To carry the workmen to and from work, and from one station to another, they provided a paddle steamer capable of carrying 450, and also used the steam barges and steam launches, and besides this they had to have a number of special trains run on the railroads.

Now we will proceed to consider a few of the details.

The entire weight, of course, is taken at the bases of the

columns that compose the towers. These columns rest on skewbacks, which, in turn, rest on the piers, *i. e.*, the column at its base terminates in a flat plate, which rests on another plate, which latter is fixed to the pier. In the case of each tower, one of the four upper plates is rigidly fixed to the lower plate, but the other three are left free to slide on their respective lower plates, in response to change of temperature, or to wind pressure, etc.

At all three stations a large amount of preparatory work had to be done to render it possible to establish the works. Thus, on the south shore, where the works were very extensive, a jetty, 2,100 feet long and 50 feet wide, was built on piles; and on this jetty a number of temporary lines of rails were laid, with sufficient space between them to store a great deal of the material as it arrived. From the shore end of this jetty an incline, operated by a rope and a stationary engine, led to the underworks, and all the material went down this incline, as well as the pipes conveying hydraulic pressure. Branches from the railroad led to all parts of the works to facilitate the delivery of the material to and from the furnaces, shops, etc., where it was operated upon. Of course, there was a full quota of cranes for loading and unloading. Not far from the jetty were laid down launching ways of timber, wide enough to take, side by side, two caissons of 70 feet diameter each. The ground where the works were placed had to be first levelled off in terraces, inasmuch as a great deal of level ground was necessary for the works. Here were established a carpenter's and joiner's shop, a large drawing loft, extensive drill roads, a great deal of space out-of-doors for erecting separate parts, and a great many shops containing an enormous amount of machinery, the greater part of it having been specially designed for these works. This plant kept on growing during all the five years that the bridge was in process of construction, so that the cost of the plant was not far from \$2,500,000. On Inchgarvie the rock all over the west end of the island had to be cut down to seven feet above high water, and ground had to be filled in and about 100 yards of

sea wall built in order to be able to erect the necessary works there. Also, the whole space between the piers was covered with staging made of iron, its area being 10,000 square yards. The verticals for this staging had to be put in place by derrick cranes, and adjusted at the bottom by a diver, and a pin projected into the rock to hold them. Indeed, the erection of this temporary work alone is worthy to be considered as quite a notable piece of engineering.

It was on this island also that the tests were made to determine the greatest pressure of the wind likely to come against the bridge.

The work was carried on night and day, and hence the entire place had to be lighted, not only the shops, etc., but also the particular parts of the bridge where work was going on. For this purpose, three complete electric lighting plants were built and operated; the one on the south shore, however, was, of course, far the larger.

From this brief sketch it is plain that there was a large amount of engineering of varied character required in establishing the works, and in making preparations for the erection of the bridge. It was like building very extensive shops, furnaces, power plants, special machinery, and providing transportation facilities for five years, with the full knowledge that the works must be no longer operated at the end of that time, but all the machinery and appliances must be sold.

Two of the piers on Inchgarvie, and all four on the south shore, had to be founded so far below low water that they had recourse to pneumatic caissons. I will give a brief description of them, and will endeavor to word my description in such a manner as to explain what is a pneumatic caisson, and how it is operated.

The caissons used in this case were made of wrought iron. Their form on the outside was that of a cylinder surmounted by a truncated cone, the diameter of the cylindrical portion being 70 feet, while the small diameter of the conical part was 60 feet; on top of this was fastened the temporary caisson.

Seven feet above the bottom, we find an air-tight floor, strongly braced. Above this floor is put concrete in such quantity as at first to cause the caisson to float with the desired immersion, and afterwards to cause it to sink. The space below the air-tight floor is in the form of a truncated cone, 70 feet in diameter at the bottom, and 56 feet at the top, this being the working chamber, or the chamber where the excavations are made. Three shafts, each 3 feet 7 inches, connect this air chamber with the top. When the caisson is in operation, one of these shafts serves for the ingress and egress of the workmen, and the other two for the ingress and egress of the materials.

Now, the height of the entire construction, *i. e.*, permanent caisson with temporary caisson attached on top, must be sufficient to reach above high water when the caisson is fully sunk. A little above the top of the permanent caisson are found the tops of the three shafts already mentioned, and at the tops of these shafts are airlocks, through which entrance into, or exit from, the shafts, and hence the working chamber, is effected.

Of course, the internal construction of the caisson would reveal a large amount of heavy bracing, but I shall not undertake to describe it. We thus have in a caisson, as it were, a huge diving bell, into the working chamber of which we force compressed air. This drives out the water, and the caisson, being so loaded as to descend just the right amount, and the compressed air being let on, the workmen proceed to make the excavation, and the material excavated is drawn up by a hoist through the shafts. After the excavation was completed, and the caisson had been sunk to its final resting place, the working chamber was gradually filled up with concrete, and also the shafts, and they then proceeded to fill the whole up with concrete to the level of low water, and at this level began the masonry piers.

The caissons were built at the launching ways, where they were riveted up with hydraulic riveters. When completed, they were launched at high tide and towed to the end of the jetty, where the temporary caisson was attached,

and the machinery, etc., was put on, and then they were towed to position.

The granite piers were begun at 18 feet below high water, *i.e.*, at low water level, and here the diameter of each pier was 55 feet, and they were built up to 12 feet 8 inches above high water, the diameter here being 49 feet.

When the piers had reached a level of seven feet below high water, a staging was built at the height of the bed-plate on which the columns of the supports were to rest. By means of this staging, and a template of the bed plate, the holding down bolts were put in place and built in. There were forty-eight holding down bolts in each pier; they were made of a special kind of steel, and had a diameter of two and one-half inches, increased to three inches at the ends where the screw thread was cut.

As much of the work as possible was drilled with all the parts put together; there were a great many special machines, as plate-bending, multiple-drilling, edge-planing, multiple-riveting and others, and portable hydraulic riveters, all specially adapted to the special work to be done.

The work of erection was first carried on to a height of fifty feet above the tops of the masonry piers, and, after that, hydraulic lifting platforms were constructed and used in the central towers. By means of these lifting platforms, the material was raised to the level required, and then it was taken to the point where it was to be used. These platforms were lifted by means of hydraulic rams placed in the central towers. Now, when the cylinder was anchored at any one height, the extent to which the platform could be lifted was the stroke of the ram. When it had been lifted thus far, it became necessary to raise the cylinder of the ram and to anchor it higher up. An ingenious arrangement, which I will not stop to describe, was devised to attain this object. A very ingenious riveting machine and cage was devised and used in doing the enormous amount of riveting which had to be performed in place.

It is plain that the engineering work involved in designing the bridge and its foundations, and making the necessary calculations and drawings, was very decidedly less than

that which had to be performed in the construction of the bridge, the latter comprising an enormous variety.

Now, this is the largest bridge in the world, *i. e.*, the one having the longest spans; but engineers are, as a rule, a progressive body of men, and they are constantly devising and erecting works of greater magnitude than any that have gone before, so that it is very doubtful how long it will remain the largest.

Of course, the amount of engineering work involved in erecting small bridges is far less than in the case of such a bridge as the Forth, but it is all a matter of degree, and the making and erecting of any bridge of any importance requires a great deal of engineering work. Thus, in the case of a moderate sized bridge more or less elaborate works must be on the ground, to handle the material and to perform the work which has to be done there, and which may involve riveting, drilling, punching and a variety of other operations.

Indeed, now that electricity is becoming so much used for the transmission of power, it is not at all unlikely that it, too, will come into play to a considerable extent in the work of erecting bridges and of building them.

Moreover, whereas the designing and building of bridges has been usually associated with the idea of civil engineering, it is plain that a large, if not the larger, part of the work is such as is usually called mechanical engineering; or, rather, it seems to me that we are forced to the conclusion that there is no one portion of engineering that belongs exclusively to civil engineering, and no one portion that belongs exclusively to mechanical engineering, but that all belong to engineering.

Time will not allow me to take up a number of other cases of what are commonly called public works, and which involve a great deal of engineering. Thus, were I to describe to you the details of the piercing of the Mont Cenis or the St. Gothard tunnel, or our own Hudson River tunnel, which, though not completed, is a work of great merit; or were I to describe the operations connected with building canals, as, for instance, the Amsterdam Ship

Canal, the Manchester Ship Canal, the Suez Canal, or even the Panama or the Nicaragua Canal, or the operations connected with the improvements of rivers, the building of ports, of docks, etc., you would find again a condition of things similar to that already explained. All these matters require a very large amount of engineering work of all kinds, and also the use of the most modern appliances in the way of machinery of all sorts, including, of course, the steam plant, etc.

*Steam.*—Such works as those already referred to have, in many cases, been carried out by the Government at public expense, and hence they have often been classed as public works, although some of them, especially railroads, are, in this country, private enterprises. It is in connection with such works as these that the common idea of engineering has been exclusively or, at least, chiefly associated. In former times works of great magnitude were almost always undertaken by the Government, because it alone could command the needful capital to execute them; or if in any case private capital was invested, it was subsidized by the Government. Works for the Government at the present day are often let out in whole or in part to private parties to execute. Moreover, this is preëminently an industrial age, and we have consequently so much engineering involved in the operations of private concerns that the total amount done for them far exceeds that done for the Government. Hence we shall, later on, consider what may be termed private enterprises. With the exception of mining and a few others, we might include most all such enterprises as involve engineering to a considerable extent under the term manufacturing.

Before entering upon a consideration of what are the engineering problems involved in these industries, I must first refer briefly to the development of the use of steam and the steam engine. To-day one can hardly undertake any engineering work, even of small magnitude, without the use of steam, and no engineering work of any considerable magnitude can be carried on without a considerable use of steam. We have become so accustomed to this state

of things that it is very hard to realize the condition of the industrial world before the general introduction of this agent, when the only available sources of power were water-power, wind-power and the muscular power of animals and men; and when we contemplate any large work of those days we are led, in expressing our admiration, to couple our words of praise with the remark, "notwithstanding their lack of facilities for performing such work." I shall not stop to consider the earliest history of the introduction of steam for power, involving the work of Hero, of Savery, of Newcomen and of others, but I cannot avoid making some mention of James Watt, for, if we enumerate the important problems that have arisen affecting the development of the steam engine from the beginning down to our own day, we shall find that almost all of them were recognized and taken into consideration in some form by Watt; and, although the improvements that have since been made are enormous, and although the economy of steam that can be realized to-day is far greater than that obtained by Watt, nevertheless the contrast between the modern engines and those of Watt, enormous as it is, is not as great as that between Watt's engines and those of his predecessors, and, moreover, one great reason for the success of James Watt lay in the thoroughly scientific manner in which he did his work. Instead of attempting to evolve out of his own mind, without investigation, a successful engine, he began by making a long and careful series of experiments by means of such an engine as was then available, and by means of other apparatus which he made for his special purposes, and, by studying the faults, the shortcomings, and the chances for improvement in the then existing state of steam engine practice, he succeeded in working out the means of remedying to a very considerable extent the difficulties encountered. He made a series of experiments to determine the actual amount of coal and water consumption per horse-power per hour in the Newcomen engines, such as were then in use in the mines for pumping water. He found the amount of coal and water consumed to be very excessive, so considerable

indeed that the cost of using such an engine was often prohibitive.

He began experimenting with the model of a Newcomen engine to which he had access, and found that the boiler was too small to furnish the requisite steam for the engine. He made a new and larger boiler, and then proceeded so to arrange the apparatus that he could determine, by actual weighing, the amount of water evaporated, and the amount of steam used by the engine in any given time.

In the Newcomen engine, steam was admitted under the piston, and thus the piston was raised; then, for the purpose of allowing the piston to descend, the steam was caused to condense, either by cooling the cylinder by water poured on the outside, or else by a jet of water introduced into the cylinder. In either case the loss was very considerable, and before he completed his experiments he came to the conclusion that in the Newcomen engine at least three-fourths of the steam was wasted, and he set about trying to get rid of this loss.

He gives, as the results of his researches:

(1) The capacities for heat, of iron, copper, and of some sorts of wood, as compared with water.

(2) The volume of steam as compared with that of water.

(3) The quantity of water evaporated in a certain boiler by one pound of coal.

(4) The elasticities of steam, at various temperatures greater than that of boiling water, and an approximation to the law which it follows at other temperatures.

(5) How much water in the form of steam was required at every stroke by a small Newcomen engine, with a wooden cylinder 6 inches in diameter and 12 inches stroke.

(6) The quantity of cold water required in every stroke to condense the steam in that cylinder, so as to give it a working power of about seven pounds on the square inch. These researches showed him what were the difficulties, and cleared the way for his improvements. His first means of saving steam was by the use of an independent condenser, and an air pump, instead of condensing the steam

in the cylinder itself. The following description of his inventions up to 1769 is given in his patent :

"My method of lessening the consumption of steam, and consequently fuel in fire engines, consists in the following principles :

"(1) That the vessel in which the powers of steam are to be employed to work the engine, which is called 'the cylinder' in common fire engines, and which I call 'the steam vessel,' must, during the whole time that the engine is at work, be kept as hot as the steam which enters it—first, by inclosing it in a case of wood, or any other materials that transmit heat slowly; secondly, by surrounding it with steam or other heated bodies; and thirdly, by suffering neither water nor other substances colder than the steam to enter or touch it during that time.

"(2) In engines that are to be worked wholly or partially by condensation of steam, the steam is to be condensed in vessels distinct from the steam vessel or cylinder, though occasionally communicating with them. (These vessels I call condensers, and while the engines are working, these condensers ought at least to be kept as cold as the air in the neighborhood of the engines, by application of water or other cold bodies.)

"(3) Whatever air or other elastic vapor is not condensed by the cold of the condenser, and may impede the working of the engine, is to be drawn out of the steam vessels, or condensers, by means of pumps wrought by the engines themselves, or otherwise.

"(4) I intend, in many cases, to employ the expansive force of steam to press on the pistons, or whatever may be used instead of them, in the same manner as the pressure of the atmosphere is now employed in common fire engines. In cases where cold water cannot be had in plenty, the engines may be wrought by this force of steam only, by discharging the steam into the open air after it has done its office.

"Lastly, instead of using water to render the piston or other parts of the engine air- or steam-tight, I employ oils, wax, resinous bodies, fat of animals, quicksilver and other metals in their fluid state."

Later, Watt patented the expansion of steam and six methods of using it; the double-acting engine; the double or coupled steam engine; the use of a rack on the piston rod, working in a sector on the end of the beam to secure a truly rectangular motion; a rotary engine. He next decided to add a fly-wheel to his engines to equalize the effect at different parts of the stroke. He then devised his parallel motion; also the arrangement of cross-head and guides now universally used. He also patented the poppet-valve; also a revolution counter; the pendulum governor and mercury steam-gauge; the water glass and the steam engine indicator.

The above gives a partial list of the devices and improvements introduced by Watt into the steam engine; and, whereas we should to-day much prefer to have a modern engine rather than an engine of that day, nevertheless, it is plain that the rate of development is not at all as great as that which represents the change from the engine of Newcomen to that of Watt. That the introduction of the Watt engine to pump water from mines, and to run mills and shops, made a complete revolution in the ways of carrying on industrial pursuits is evident, and equally so that to the work of Watt is due the development of the steam-boat and of the locomotive. Indeed, it was one of Boulton & Watt's engines that Fulton placed in the *Clermont*, to drive it when he made his memorable first voyage up the Hudson, in 1807.

Whether, therefore, we consider railroads, or navigation, or mining, or manufacturing of any kind, or applications of electricity, we find that the steam engine has revolutionized the industry, and that no one to-day can undertake engineering work of any magnitude without having to make use of steam.

Now, without stopping to consider further what was the work of the early days—of Watt, of Fulton, of Stephenson, and of the host of other men who had a part in introducing and developing the steam engine—let us consider what have been the later developments that have been made in its use.

And here we may say that the entire impetus towards an

investigation of the defects of the steam engine and the remedies therefor, has been the desire to save coal, and hence to cause the engine to do its work, and to make the boiler produce the necessary steam, with a smaller coal consumption. Economy of coal became at once an item of the greatest importance in the case of the marine engine, for every ton of coal less not only saved the expense of the coal, but also space in the vessel for carrying cargo, which was profitable freight. Indeed, in the early days of the marine engine, one of the questions raised touching its practicability was whether it was possible to carry enough coal for a long voyage. Hence it is that we find on the whole that improvements and economy were more sought after in the case of the marine than in the case of either the stationary or the locomotive engine.

Another fact that has aided in making the improvement of the marine engine more rapid than that of either of the others, is that the work done by it is more nearly constant; and, besides this, when the boat is on a long voyage the engine runs night and day, so that the fires are not put out each day, and rekindled as often.

Next to the marine engine, in this regard, stands the stationary engine, and especially the large pumping engine; although, in the case of the small pumping engine, economy of steam and hence of coal is usually sacrificed to cheapness of first cost and ease of repairs.

Why more attention has been paid, until lately, to economy of steam in the case of the large pumping engine than in the case of other stationary engines may seem strange, but the reason is probably to be found in the fact that such engines are necessarily owned either by the Government or by some rich corporation, whereas it has only been with the enormous development of manufactures that belongs preëminently to more modern times that large engines have been required to any great extent in manufactories, and even to-day we often find in use, in a large manufactory, a number of small engines in many cases in which the substitution of one large one would make a decided saving of coal.

In the earlier engines the valves were set to cut off at some definite point, and the steam supply was automatically adapted to the load on the engine by means of a throttle governor, which varied the pressure of the steam when it came into the cylinder. The first attempt to do away with the losses consequent upon the throttling of the steam was made by George H. Corliss, of Providence, who caused his governor to regulate the point at which the steam should be cut off, and, therefore, he left its pressure as it came into the cylinder undisturbed.

Though this is not one of the earliest improvements, it is, nevertheless, one that has been very far-reaching in its effects, and it is rare to-day that we find any large engines that throttle their steam, as large engines are almost invariably provided with an automatic cut-off.

Indeed, the influence that Corliss exercised on stationary engine practice was very great, and, throughout Europe and America, we find that the Corliss type of engine is very extensively used. But while much may be said in favor of the rotary valves and the drop cut-off, which are so characteristic of the Corliss style of engine, Mr. Corliss, nevertheless, was not identified to any extent with the modern compound and triple engines.

The saving that could be obtained by using steam expansively, instead of allowing it to follow the piston throughout the stroke, was recognized by Watt, and this feature is to be found among the early engines, and so deeply were engineers impressed with it, that they began to build engines to run with shorter and shorter cut-offs, expecting to save steam thereby; but, later, attention was called by a number of engineers and others to the fact that cylinder condensation was an important item to consider, and that with very short cut-offs the effect of cylinder condensation was to bring about a waste of steam; so that, for every different engine running under definite conditions as to steam pressure, back pressure, etc., there is a certain cut-off which produces a greater economy of steam than either a longer or a shorter one.

To explain to any one not familiar with these matters

what is meant by cylinder condensation, I will say that the steam, when it enters the cylinder, is very hot; thus, steam of 100 pounds (*i. e.*, 114·7 absolute) pressure, has a temperature of  $337^{\circ}\cdot 7$ , and, when it leaves, it has a low temperature; thus, if it escapes into the air, its temperature is  $212^{\circ}$ , or if it escapes into a condenser it is even less.

Now, during a given stroke, the steam on one side of the piston has been escaping into the air or into a condenser, and the metallic walls of the cylinder have been exposed throughout this stroke to this low temperature, hence they must have cooled off considerably and be very much colder than the steam which enters immediately afterwards, at the beginning of the return stroke.

When the steam enters at a high temperature and comes in contact with the cold metallic walls, its first function is to condense and heat these walls, and hence a large amount of steam is condensed in heating up the walls of the cylinder instead of performing work. Now, this cylinder condensation, as it is called, is greater, the greater the difference between the temperature of the steam when it escapes into the air or into the condenser, and that of the incoming steam, and anything that can be done to decrease that difference will decrease the loss due to cylinder condensation. If the cut-off is made shorter and shorter, the gain due to using steam expansively is soon offset by the greater loss due to cylinder condensation.

It is the consideration of the losses due to cylinder condensation that has, perhaps, more than almost anything else, brought about the more recent improvements in the steam engine, both marine and stationary, and now it is also beginning to have its effect in the case of the locomotive. There are several who claim to be entitled to the credit of first pointing out the fact that cylinder condensation exists, and it is not long since a number of articles appeared in the scientific papers claiming the credit respectively for Isherwood, for D. K. Clark, and for Hirn. It is not of any special interest to us to settle this question.

As to the fact that cylinder condensation exists, James Watt found that the chief source of loss in the Newcomen

engine was cylinder condensation, and that was the first thing he undertook to remedy, thereby saving as much as three-fourths of the steam used by Newcomen's engine.

The thing of real importance for us, is to have a number of well-arranged and careful scientific experimental investigations to determine its amount under a variety of different conditions, so fully as to give us reliable information as to how to reduce it to a minimum.

Now, neither of the men mentioned above has made any such complete series of experiments, nor has any other one man done it, but it is a matter in regard to which, through the exertions of a great many, we are making decided progress, and the chief set-back is due to the attempts and claims of those who, ignoring the good example of Watt, make experiments in an unscientific or careless way, and put forward as true, conclusions that are not, and which, if accepted as facts, lead to costly experiments and certain failures. Nevertheless, a good deal of progress has been made, and the world is very much alive to this question to-day. The result has been the adoption long ago of the compound marine engine, and of late of the triple expansion marine engine, so that we find on almost any large steamer either a compound or a triple engine.

In stationary engine practice, the compound engine has frequently been used for water-works engines, but it is only in later years that it and the triple expansion engine have been introduced to any great extent into mills and manufacturing establishments in the United States; and it is only very recently that the compound principle is being introduced into locomotives. A compound engine is one in which the steam performs only a portion of its expansion in one cylinder, and then it enters another and a larger cylinder at a lower pressure, and completes its expansion therein. The result is that the difference of temperature in each cylinder between the entering and the departing steam is less than it is when the expansion is completed in a single cylinder, and therefore the cylinder condensation is less. In the case of a triple expansion engine the expansion is only completed in three cylinders, the

steam doing work in the first, then entering the second at a lower pressure and expanding therein, then entering the third at a still lower pressure, in which last the expansion is completed.

The one reason for expanding in more than one cylinder is to diminish cylinder condensation, while taking advantage of the expansive force of the steam.

Now, in regard to the progress being made in the matter of economy in engine construction, some of the questions that naturally arise are, in any given case:

- (1) What degree of expansion should be used?
- (2) Is it best to use, under the conditions in hand, a non-condensing, a condensing, a compound, a triple expansion, or a quadruple expansion engine?
- (3) If a multiple expansion engine is decided upon, what should be the proportions between the different cylinders?
- (4) Should receivers be used, and of what capacity?
- (5) To what extent and in what way should steam jacketing be carried out?
- (6) What effect, if any, has the piston speed, or the rotative speed on the economy of steam?
- (7) Is it better in any given case to adopt a jet, or a surface condenser?
- (8) What kind of boilers should be used, and what should be their proportions?

All the above are questions which concern the economy of coal and water; but there are of course many other questions to be answered and conditions to be considered; such as—

- (9) What degree of regularity is it necessary to maintain, and how shall we build the governor and the fly-wheel to attain it?
- (10) All parts bearing loads must be made of the requisite strength, and the stresses should be carefully calculated so as to secure safety.

As an instance of carelessness in this regard, I need only call attention to the fact that every now and then we hear of some fly-wheel that has burst, has killed a number of people, and destroyed a great deal of property, and I will

say that I have found a number of wheels where it is evident that the stresses were not properly calculated by the designers, and where there is a very small factor of safety, and consequently a large element of risk, and I do not doubt that a proper care in the design would avert a number of the accidents that occur.

Another instance where the better class of builders do take at least a fair amount of precaution as a rule, but where, in many cases, great risks have been taken, is in the case of steam boilers, though the accidents due to steam boiler explosions are attended with so much danger that more effort has been made to exercise a proper supervision in their construction. Indeed, the steam boiler insurance companies exercise a considerable check on the existence of dangerous boilers.

Reverting to the questions concerning the economy of coal and water, a great deal more is known to-day than formerly, and the increase of knowledge on the subject has operated in causing material improvements in engines, particularly for large plants; nevertheless, the complete answers are to be determined in the light of careful and scientific experiments, and these questions now are no longer to be decided by rule of thumb, nor by haphazard trial. They are no longer questions for the inventor to solve, but require the best efforts of the engineer. The really scientific work on this subject is of very recent date, but those who take the responsibility for the expenditure of large amounts of money for steam plants are ever on the alert to get the benefit of any such experiments.

In considering the second question, for instance, the decision must depend upon what other use, if any, is to be made of steam.

Thus, if a very large amount of steam of a very low pressure is required, it may be that it will be more economical to use a simple non-condensing engine in certain cases, rather than a compound, and then to utilize the exhaust steam for the other purposes, as, for instance, for heating; for the exhaust steam is practically as efficient for heating as live steam, and hence, in cases where all the exhaust

steam is used for heating, if we estimate the expense of our power, in coal, at five per cent. of what it would cost if the exhaust steam were not used, we shall have made a large estimate.

Some attempts are now being made to use stationary compound engines with not very high initial pressures, exhausting into the air, or against a small back pressure, and considerable economy is claimed for them. They are now in the experimental stage, however, and it is too early to give a very positive decision in any cases that have thus far been developed. Nevertheless, in locomotive practice, the case is precisely one where the exhaust from the low-pressure cylinder takes place into the air, but in this case the initial pressures are very high, and while the experiments that have been made have not been as full nor as accurate as could be wished, enough has been done to show that a decided saving of coal can be obtained in many cases by the use of the compound locomotive when properly designed and operated.

Another matter that requires the careful consideration of the engineer is how to transmit the power from the engine to the different places where it is to be used, and to see that all this is properly designed. This, in some cases, is accomplished by gearing, in some cases by belting, and in many cases by ropes running in grooved pulleys.

Now that electricity is coming to play such an important part in all our engineering operations, I do not doubt that there will soon be cases where the engine will be employed in driving one or more dynamos, using up a part or the whole of its power, and then the power will be transmitted to the different points where it is needed, as the different floors, or the different shops, or to the different groups of machines, and sometimes perhaps to the different machines themselves by a wire from the dynamo, connected at the other end with an electric motor.

There is no doubt that a large engine can be run with much greater economy of coal than several smaller ones delivering in all the same amount of power; hence it is desirable, whenever there are not other reasons which offset it, to concen-

trate the power plant in one place, and in cases where this is not possible, to do as much as can be done towards concentration. In many cases it cannot be carried out, and in others it can only be done partially; nevertheless, if the power is transmitted by electricity this will be an aid towards such constructions.

Next comes the question of boilers. The contrast between the boilers used at or about the time of Watt and those used to-day is very marked. The pressures in use were very low, and boilers could be made of most any material and of most any shape. Copper was a favorite material, and Watt, in some of his experiments, even tried wood. Later on, cast iron came into use, and later still, wrought iron and now steel has almost displaced wrought iron in boiler construction. Of course, cast iron is still used in many sectional boilers, and in some of the complicated fittings of cylindrical boilers. The early boilers were made without any special pains being taken to calculate their strength, and the pressures were increased by those who used them with so much carelessness that there were a great many accidents.

As pressures rose, however, it became more necessary to look after the matter of strength carefully, and this fact began to have its influence in the shapes and designs of boilers. But even when pressures had reached thirty or forty pounds per square inch, there were still in use a great many marine boilers having a number of flat surfaces which, of course, had to be stayed, but now the pressures have increased to as much as 150 and even 200 pounds, and it has been necessary to adopt the cylindrical form for the marine boiler, so that the marine boiler has changed enormously since early days.

Of the different types of stationary boilers there is no end, but all of them are very different from the boilers of early days. Moreover, pains are taken to-day to avoid loss of heat; thus economizers are frequently introduced, by which the feed-water is heated by a portion of the waste heat which would otherwise be lost by going up the stack; pains are taken to lag the boiler if it is internally fired,

or to make some provision in any case to prevent the escape of heat; the pipes are covered, and precautions are taken to save heat in every possible way. Also, the feed-water is very commonly heated by exhaust steam, or otherwise. Then, in establishing a power plant the chimney demands consideration. It must be adequate for the boilers, and it must be properly constructed.

Provision must be made for receiving and storing coal, and this should be arranged so as to save labor, as far as possible, and to deliver the coal as near the boiler as is feasible.

Another use of steam which presents itself is the heating of buildings, and this has to be done in many places where no power is needed and no engine is run, except a pump to feed the boiler, and perhaps an elevator may be run by power derived from a small engine or pump. In this case there used to be but one way of effecting the heating, viz.: to place radiators in the rooms to be heated, and to convey steam to these radiators by pipes. Now, however, ventilation is considered an important factor, and systems of heating are adopted which provide for ventilation at the same time.

I will explain one of these systems as exemplified by what is done in the Engineering building of the Institute of Technology. Steam is used in the building for heating and for power; it enters through the main pipe and passes through a separator before continuing on to the engine; water and wet steam are drawn from the bottom of the separator and put into the heating system, and so is also the exhaust steam from the engine, when the latter is not condensed in the condenser. Besides this, live steam is used whenever there is not enough of the other. The steam passes into the various coils, which will be described. There is, in front of an opening in the wall, the main coil, and in front of that a fan run by a special small engine. This fan draws air in through the coil, *i. e.*, around the pipes forming the coil, and thus the air becomes heated. Then the air is driven by the fan into a duct, which extends all around the sides of the basement into which it is delivered in a slightly

compressed state. This duct is connected with a number of upright channels leading to the various rooms of the building, all of them being lined with tin. At the base of each of these vertical ducts is an auxiliary radiator, to which steam is admitted, so as to add more heat to the air, in addition to that which it received from the main coil. Then there are registers in the uprights which open into the different rooms, also other registers which connect the rooms with outlet flues. Thus, the rooms are heated by the warm air introduced into them. Moreover, there are a number of direct radiators in addition, to provide for more heat in very cold weather. There is also an arrangement for automatically regulating the temperature, so arranged that when it rises or falls a certain amount,  $1^{\circ}$  above or below the normal, an electrical connection is established, which causes compressed air in a small pipe to close or open the steam valves of the direct radiators or the registers in the case of the indirect system.

There are many other methods of using steam for heating, to which there is not time to refer. Neither is there time to dwell further upon the almost countless uses for steam in connection with the industries and with the civilization of the world.

In the preceding lectures, all the illustrations which have been used are commonly recognized as engineering works, though some are often classed as civil, and some as mechanical engineering. I have endeavored to show that the distinction is a purely artificial one; that the civil engineer who is to carry on responsible work, cannot get along without what is commonly called mechanical engineering; that the science of engineering is one, though very extensive in its range, and that the history of the development of engineering up to and in modern times is the history of the development of machinery, whereby we direct the great sources of power in Nature for the use and convenience of man. In this lecture, I propose to present to you a very brief view of the part that engineering work plays in what are commonly called the industries of the world. Of course, any presentation which I can make in an hour

must be very incomplete, and I shall choose only a few illustrations, and leave them to serve as examples of a much larger number.

And first, before taking up any manufactures, I ought to say a few words about mining.

I suppose that, in the popular mind, mining operations have generally been intimately connected first with geology, second with chemistry, and but slightly with engineering; but, if we stop to examine the actual condition of things, we shall find, I think, that, whereas there are cases where the man who has charge of a mine, or of a metallurgical works, needs to give his own attention primarily to metallurgical, to chemical, or even to geological questions, and where engineering questions are a secondary consideration, the cases are more frequent where much the larger part of his attention needs to be devoted to the engineering questions that arise in the work.

Geology serves to locate the mine, and to inform him what he may reasonably expect to find within the bowels of the earth, and what is the precise location of the deposits, so that he may know what excavations to make to reach them. It teaches him also the nature of the neighboring layers, and the difficulties he is liable to encounter in consequence of the characteristics of these materials; but all the exploration is largely completed before the mine is opened, or, at least, it is usually finished for any portion before the works are commenced on that portion, so that the amount of geological work to be done during the operation of the mine is generally not large.

Chemistry tells him the composition of his ores and of his product, and hence gives him the means of determining how to mix and how to treat them, but any one mine is dealing with one kind of ore, and any one metallurgical works is conducting a certain special kind of operations, and, therefore, the chemical work required in connection with them is limited to certain narrow lines. The result is that, after the works have been running for some time, the chemical work, while it requires careful attention, is, nevertheless, largely a matter of routine; to carry it out are

required men well drilled in this routine, and it is not necessary that they should be expert chemists, for, if a problem occasionally arises which is outside of the routine, and of sufficient consequence to warrant it, an expert chemist can be employed to solve it.

When we come to the case of metallurgical works, of course the man who is to manage them must have the necessary knowledge of metallurgy—of that kind, at any rate—or else he does not know his business, and he must devote whatever time and thought is necessary to all the metallurgical questions that arise which are not matters of routine, for those that are can be performed by men skilled in the special work, the manager only exercising enough supervision to see that these matters proceed correctly. When this is done, the problems that ought to engross the larger part of his time will depend upon the nature of the works. In some of them metallurgical problems will absorb more of his time than engineering, but in the greater number of such works the engineering problems will demand a larger part of his time and thought than the metallurgical, if he is to run the works with the best results.

Now, in the case of the engineering work, new problems are constantly to be solved, new emergencies are constantly to be met, for the mine must be kept running both economically and efficiently if the work is to be properly done; and if the works are large the engineering work assumes very large proportions. Some of it can be done by the manager personally, but a very large amount he must delegate to assistants, and these assistants must understand engineering.

In order to make plain how large an amount of such work has to be performed, I might say that in the case of a mine of any sort, unless it is very small, there is water that must be removed; hence, there must be machinery for pumping; the material mined must be lifted out of the mine, and the miners and various supplies must be carried in and out of it; hence, hoisting machinery of some sort is needed; rock drills must be used, and these are driven

by compressed air; hence, air compressors, and suitable engines to drive them; the men must be furnished with fresh air and the foul air must be removed; hence, some sort of ventilation must be provided. All this is necessary in any mine, besides timbering or walling the shafts and certain galleries. Then when the ore has been hoisted it must be broken up and prepared in various ways before it is ready for the furnace, and in many cases the works for preparing it—commonly called the mill—are not far from the mine.

Confining our attention first to the mine itself, we find, in regard to the pumping, all sorts of methods in operation, some very wasteful, and others varying in economy in every conceivable degree, according to the amount of engineering knowledge, and the judgment of the mine engineer. Thus, he may use direct-acting pumps at the bottom of the shaft, and at intervals along it, but the engineer knows that these are very wasteful of steam, and hence of coal; or he may bring to bear his engineering knowledge, and put in whatever will be most economical under the circumstances, be it a triple or a compound engine to do the pumping. The details of the arrangements of pumps and pump rods, and their connection to the engine, are all matters that must be attended to. Then, in regard to hoists, there is great room for choice, and a good opportunity for the engineer to exercise his talents. Probably the most instructive example apropos to this phase of our subject is afforded by the hoist now being put in the Calumet and Hecla mine. This machine is to lift ten tons of ore at the rate of sixty feet per second, through a height of 6,000 feet. The engine is triple-expansion, with cylinders  $20\frac{1}{8}$ ,  $31\frac{1}{4}$  and 50 by 72-inch stroke.

At this mine many modern appliances have been introduced, among others three hoisting engines, which are triple-expansion, with cylinders 18,  $27\frac{1}{4}$  and 48 by 90-inch stroke. In order not to interfere with the work of hoisting the ore, a separate engine is usually provided to run the man hoist, which may be the regular man engine, or may be a car drawn by another hoisting engine. Then comes

the choice of compressors and engines to run them, their erection and operation; then the means of ventilation, whether by natural draught or by an exhaust fan.

All this, of itself, if the mine is of any considerable magnitude, means the establishing of a large plant of machinery, and hence all the engineering work and all the engineering features necessarily involved in the erection and operation of such a plant, besides the engineering work that relates particularly to the special machinery in use and the special work to be accomplished by it. There must be, of course, a suitable boiler house and chimney, and suitable boilers must be erected and operated with whatever adjuncts, as economizers, etc., it is thought best to use, the conditions here being exactly the same as they are in the case of any boiler plant, and hence, engineering questions. Then the principle which directs the engineer to concentrate his power in one place, as far as possible, and hence to use one large and economical engine instead of several small and wasteful ones, applies here as it does to any power plant. How far this concentration can be carried must depend upon a consideration of the special conditions of the work; and all this involves, of course, a consideration of the arrangement of the works and of the system of power transmission. Of course, the arrangement of the power plant will probably be affected by the manner of getting the power from the engine to the pump rods or man engine rods, or rope drive, etc., that carry the power to the shaft.

In all these works, in the erection of the buildings, in putting up the machinery, etc., as well as in making suitable constructions to hold it, and in timbering or walling the mine, maintaining the works in serviceable condition, etc., questions of strength of materials are constantly coming up.

Then, again, the engineer must consider the means of handling the ore as it comes from the mine, and of transporting it to the place where it is next required. Then, if it is to go to the mill, it must be carried there, or, if it is to go to a distance, must be loaded into cars. Of course the

engineer will take advantage of the force of gravity whenever he can do so, for that costs comparatively little.

Next, as to the mill. Here the nature of the machinery will depend, of course, upon the particular kind of ore being treated.

We have first the ore dressing, and this involves the exercise of a very large amount of engineering. In certain cases the crushing is done by a stamp mill, in others by crushing machines or crushing rolls. Then come the arrangements for sorting the coarse from the fine, for separating the part which contains valuable material from that which does not, sometimes by gravity, sometimes by amalgamation, sometimes by magnetism, etc. Then, if the mine is large, the waste material must be removed, which is done by means of lifting or transporting apparatus, as, for example, the sand wheel.

Moreover, in any process of concentrating, a large amount of water will be needed, besides which it is also necessary for the boilers and for other purposes. Hence it becomes necessary to find a suitable water supply, and to set up the pumping engines required, etc.; in short, to establish a water supply, and finally, the waste water must be disposed of. Now, these engineering questions are everyday matters, and wastefulness or inefficiency here means expenditure with no return, hence all the coal that can be saved, all the labor that can be saved, all the saving that can be made by avoiding the doing of useless work, all the saving of unnecessary handling, will all show their influence in the dividends of the stockholders and in the successful operation of the mine just as truly as will the adoption of the proper treatment of the ore instead of an improper one. Of course, in any particular case, it becomes a question whether we will put in the best machinery, and thus economize in the running expenses, with, however, a larger first cost; or whether we will save on first cost at the expense of economy later on. Usually, if the owner lacks confidence in the amount of the ore in the mine, he will be wise to save on first cost. But if he knows that the mine will succeed, his best course is to put in the most economical

machinery, notwithstanding that it is more expensive at first.

Next in order come metallurgical works. Of course, the treatment of the materials by metallurgical processes which will produce the proper result is the primary purpose of the works; but these processes cannot be carried on without buildings, furnaces, steam or water plant, power transmitting machinery and apparatus, the erection and operation of all of which involve engineering questions which, if neglected by those who operate the works, are sure to result in disaster. As an example, suppose the owner of a blast furnace should insist on burning coal under his boilers instead of utilizing the waste heat from the furnace, this would simply be throwing away so much heat, and hence so much money. Now, when competition becomes sharp, the man who can make a saving in any way is the gainer; and if unsuitable or weak buildings, or unsuitable or weak machinery, or lack of economy in steam, are tolerated, or if care is not taken to save labor as far as possible, the neglect is sure to result in loss; and it is the fact that people are beginning to realize the truth of this statement that is causing the proprietors of such works to pay more and more attention to their engineering features, and to seek men who are familiar with the principles of engineering, instead of attempting to carry on the engineering portion of the work with the aid of men unfamiliar with these principles, and hence liable to make serious and costly mistakes.

Now, in regard to the metallurgical and chemical processes, there is always a certain portion at least of these that, after the works have been running some time, become largely matters of routine, varying only within certain narrow limits; and these, while they need careful attention and skill, can be delegated to a superintendent, whose business it is to attend to this part of the work.

There then remains that portion of the metallurgical and chemical work which is not reduced to a routine, and all the engineering work (which can never be reduced to a routine), to be attended to.

Now, the relative proportion of time and attention

required by each of these for its proper conduct, will depend upon the nature of the works, but it is my belief that in the greater number of cases, more time and attention is required for the engineering if the works are to be run economically and efficiently; but be this as it may, in no case can this branch of the work be neglected without loss.

My time is so limited that I shall only present for your consideration one illustration of a metallurgical works.

The discoveries and inventions that have furnished us the means of making cast iron, wrought iron and steel on a large scale, and cheaply, have had an enormous influence upon the industrial progress of the world.

In the early part of this century wrought iron was not used as a structural material to any such extent as it has been in recent times, and it was not until about the middle of the century that it began to come into common use for beams, for columns, for boilers, for bridges, and for many parts of machinery. But when once introduced, it became the great structural material of the age, and has held its sway ever since, until now, when steel is rapidly displacing it for many uses.

So long as steel could be made from wrought iron only, as by the crucible process, it was altogether too expensive a material to use in construction, but the introduction of the Bessemer process, by which it is made directly from cast iron, so cheapened it that steel rails at once came into use; and since that time the development of this process, and also of the open hearth or Siemens-Martin process, where a regenerative furnace is used, and where the steel is made from a mixture of pig iron and scrap or ore and other ingredients, have so far improved, that now our boilers are made of steel, and steel beams, steel ties, steel shapes, steel shafts, and steel for most pieces of machinery, which heretofore have been made of wrought iron, are fast coming into use.

Now steel works may, and very commonly do buy their pig iron from some blast furnace works, and proceed to melt it in a cupola, and then, if they have a Bessemer plant, to make it into steel, or, if an open-hearth plant, to put

it at once into the furnace. But at some of the larger works, both in America and abroad, they have a plant which includes the blast furnaces, and which, starting with the ore, makes it into cast iron, and then, without allowing the melted iron to cool, converts it into steel; then rolls it immediately into the finished form of rails and other commercial product. In other words, the iron is not allowed to grow cold from the time that the ore first enters the blast furnace until it has become a finished rail.

Such a plant as this is that of the Maryland Steel Co. These works have been quite recently built, and great care has been taken to introduce the most modern ideas and appliances throughout.

The ore used is foreign ore, brought to the works by water, and as it is unloaded from the boat it is loaded into cars having a hopper on the bottom, which can be opened to dump the load. There is a railroad track running up over a series of pockets or bins, and the loaded cars are run up on this track to the proper place and the ore is dumped into these pockets or bins. From the bottom of these bins shutes extend downwards nearly to the ground, and through these shutes the ore is delivered on the ground in such small quantities as may be required. The coal and other raw materials consumed by the works are treated in a similar manner, some of the bins being used for ore, some for coal and some for flux. The ore, the coal and the flux, in turn as they are required, are shovelled into small, narrow-gauge truck cars, which are run upon a platform scale and weighed, the amount on the truck being adjusted by adding or by taking off some of the load while the car is still on the scale. The truck is then run upon an elevator, and raised to the top of the blast furnace. There are two such elevators, side by side, one of which rises when the other descends, their weights balancing each other when they are not loaded.

There are four large blast furnaces. When one car, the bottom of which is so arranged that it can be opened to dump the materials, arrives at the top, it is run on a track to a point over the top of the furnace, but to one side of the

center; the next load being dumped on the other side of the center, insures an even distribution. Two trucks go up at once on an elevator, and there is room for both on one track over the furnace. The bottoms of the cars are opened, and the materials are dumped around the edges of a cone-shaped cover. Then, when the charge in the furnace has sunk low enough, as determined by sticking a long poker through a small hole in the cover, the cone is lifted, and the charge drops down. The lifting of these covers is accomplished by gearing and chains, which, of course, requires some power to operate.

The boiler plant is large, and contains a number of large sectional boilers. The waste gases from the blast furnaces pass out through a flue which starts below the cone already described, and then are conveyed to the boiler house, where the necessary flues and dampers are so arranged that, by manipulating the latter, the hot gases can be conducted under any one, or under several of the boilers, or sent directly into the stack. These boilers furnish steam for all the purposes for which steam is used, *i. e.*, for running the large compound vertical engines which produce the blast, for running the pumps and air compressors, etc. Water is circulated around the furnace to keep it from becoming too hot.

The furnace is tapped at the bottom, and the melted iron runs out, and, if they are making pig iron, which they can do, they would let it run into the usual trenches on the ground, known as the sow and pigs, or, if it is to be made into a rail before it cools, it is run from the furnace into a ladle, which, with its charge, is carried on a truck drawn by a little locomotive to the Bessemer plant. Here the charge is poured into a large chamber or reservoir, called a mixer, which thus contains a store of melted cast iron to be drawn from as needed.

Near the mixer are some small cupolas, where some pigs are melted. A charge is now drawn off into a ladle, this charge being often a mixture of metal drawn from the mixer and from the cupola. This ladleful of metal is now poured into a Bessemer converter while it is on its side. Then the

blast is turned on and it is then placed in the erect position, and at once we see flames shoot out of it. The flames at first burn off the silicon; when this is burned out, and the carbon begins to burn, the flame becomes white, with purple streaks; at this point some scrap is often thrown in if the temperature becomes too high. When, finally, the carbon is burnt out, the flame drops and then a ladle hanging on a hydraulic travelling crane is brought up near the converter, the latter is turned down, and the metal is poured into it, some spiegeleisen having been first added in the converter. The spiegeleisen is a cast iron having a variable but known quantity of manganese and carbon. The converter is now turned over, and the metal is poured into the ladle and carried by the hydraulic crane to a position over the ingot moulds, which are on trucks on the ground; and the melted steel is allowed to run into the ingot moulds through a hole in the bottom of the ladle. The trucks carrying the ingot moulds and ingots are drawn by a little locomotive to the rail mill, near the entrance of which there is an ingenious mechanism for stripping the moulds from the ingots. The ingot is then placed in what might be called a reheating furnace, *i. e.*, one in which heat is applied for the purpose of imparting to it an even temperature throughout. After this the ingot is taken by a hydraulic crane and deposited in a tilting box by means of which it is placed upon the apron of rollers which deliver it to the rolls; then it follows one rolling process after another till it is formed into a rail. Without stopping to discuss the arrangements here, it is plain that not only economy of heat and steam has been taken into consideration, but also economy of labor in handling, besides which a host of engineering problems have been worked out, and are constantly to be worked out. In connection with these works they have established an iron ship-building plant, and are adopting such arrangements as will make it quite extensive when completed, but I shall not describe or comment upon this.

Let us take as our next illustration a textile manufactory, and, as an example, a cotton mill. Here, if we follow

the successive steps of the process, we must receive the cotton, unload it, weigh it and store it, separating the different grades. Then, from the storehouse it is carried to the heaters, and, after the bags and hoops are taken off, it is beaten, then passes to the pickers, from there to the carding, then to the slubbing, then to the roving, then to the spinning, whether mule or ring spinning—or some to one, and some to the other—then to the spoolers and warpers. Then the warp goes to the slashers, where it is sized and dried, and then to the looms, where it is woven into cloth, after which it may be treated in various ways. Thus, it may be finished for the market by singeing or shearing, or it may be bleached, or dyed, or printed.

Now, in planning a mill, the first thing to be considered is a proper mill site.

In choosing a site the engineer must consider especially the ease and cost of transportation of raw materials and fuel to the mill, and of the finished product from the mill to the market. If it is near tidewater or near a railroad center it will be favorably situated on these accounts. Nearness to the market, and to the base of supplies, or a situation on a stream where there is an abundant water-power available for the mill, are advantages to be taken into consideration.

Now, when the site has been fixed upon, he must proceed to lay out his mill on paper, and in doing this he must first decide upon the kind of work the mill is to perform, and hence the kind of machinery that is to be used for each process, and the number of machines of each kind, their floor space, weight, etc., also the number of stories of the mill, and also what shall be its dimensions. These latter questions may be determined by the size and shape of the lot of land available, but considerations of light have to do with the determination of the proper width of the mill. He must then proceed to locate his machines on paper so that the processes shall follow each other in proper succession, and so that the material shall pass from one process to the next with as little handling as possible, and a saving in this regard is of very great importance.

When the machinery is all laid out he must arrange his

transmission, shafting, pulleys and belts, and decide upon the position for his engine house and boiler house, his belt tower, and his transmission system. Then he must arrange his machines, so as to give the necessary space between and around them for working, and the pulleys on the shafting for driving the machines, so that there shall be no interference.

Of course, the storehouse must be planned and its position relative to the picker house. When this is all done he can determine upon the size of the mill and the position of the walls.

Then he has to determine the probable amount of power required, and thus the size of the engines and boilers.

In all of these determinations he must allow for a reasonable amount of growth, and consider what changes would have to be made, and see that the mill is so built as to admit of them.

Then the engine and boiler house must be planned, the belt tower, and the walls and columns and floors and roof of the mill, and then also its foundation. Also proper regard must be had for protection from fire.

He must ascertain what is the foundation on which he has to build, and he is liable to find that it varies at different points, and that while under some parts the foundation is good, under others it is poor, and he may have to resort to any of the usual engineering expedients to build upon it. Then, of course, the dimensions of the walls, columns, floors, foundations, etc., must all be calculated so that they shall have the requisite strength and stiffness.

Then the work must be executed, and he must see that the materials delivered on the ground are good, and that the work is properly done in all its details.

In determining upon the necessary steam engines and boilers he must take into consideration all the uses for steam in the mill. Thus, there is the heating and possibly ventilating, and also the slashers that require steam, besides which more steam will be required if there is a bleachery or a dye works connected with the mill. According to circumstances we might decide upon one or another kind of engine.

Whatever system of heating and ventilating is adopted must be planned, and all the piping, fans, etc., must be put in and fitted.

Then there must be some source of water supply, capable of furnishing water for the boilers, for drinking, for sanitary purposes, and for a variety of other uses about the mill. Then the drainage must be attended to. After all is built and arranged and the mill is running, questions are always arising as to how certain things can be improved, questions of what oil to use for lubrication, also questions of improvements in the machinery, repairs, etc. And all this is besides the carrying out of the series of processes for which the mill was built and for which it exists. But these processes become, to a very considerable extent, routine matters, though they must be carefully watched and improvements and adaptations made when needed. The superintendents must watch them carefully and must be men skilled in their own departments, and the one who has charge of the mill must also concern himself with them, but his engineering work will usually be larger in amount than the work that he has to perform in direct connection with making the fabric.

Let us now consider briefly some of the functions of the electrical engineer, and the character of the work commonly known as electrical engineering.

The present extensive applications of electricity are of comparatively recent growth, and it is only of late years that such applications as are intimately connected with the work of the engineer have been developed to any great extent.

The realization of this class of applications is due especially to the great development of the methods for the electric transmission of power, and to the extension of electric lighting; although various other applications, such as electric welding, the telephone, the telegraph, railway signaling, etc., are also closely connected with engineering work.

Heretofore the civil engineer, or the mechanical engineer, so called, has not considered electricity as an essential part

of his work, but as something which he need only cultivate if the special work in which he was engaged led him in that direction. But the signs of the times seem to be that before long the engineer will be so likely to meet with the use of electricity in one form or another, whatever be the special line to which he devotes himself, that it will become an absolute necessity for him to have a certain amount of training in that subject, as well as in such general subjects as mechanism, strength of materials, steam and hydraulics.

However, the term electrical engineer to-day is used to denote a mechanical engineer, having special training in the theory of electricity and its applications, and whose special work is in the line of the practical applications of electricity. The greater part of his work is the usual work of the engineer, the remainder having to do directly with electrical appliances. It must be borne in mind that electricity, when used on a large scale, must be generated by some external source of power, as by a water wheel, or more commonly by a steam engine; that dynamos and electric motors cannot be operated without a power plant; also that the object of electric motors is to drive machinery of some sort.

Suppose, for instance, that the electrical engineer is called on to establish an electric light station. The engineering problems arising are, in a certain sense, similar to those which would arise in building and equipping a large factory, his special machines in this case being the dynamos and connected machinery and apparatus, the manufactured product being the light. He must determine the number, size, kind, etc., of his dynamos, switchboards, etc., having regard to the requirements of the service, to the amount of light he is liable to be called upon to supply, to the district in which the lights are situated, and making allowances for a reasonable growth. All this deals directly with the electrical side of the work. He must then proceed to locate the machines, having due regard to the work to be performed, and also to the arrangements of shafting, belting, pulleys, etc., by which they are to be connected with the source of power. These last are purely engineering questions.

Then he must locate and arrange his power plant; boilers, engines, etc., determining what kinds, what sizes, and how many he will use.

Then comes the arrangement of the whole system of power transmission from the engine or engines to the dynamos. Then comes the erection of buildings to contain the machinery, in which due consideration must be given to the questions of strength, of stability, of lighting, of heating and of ventilation; also to securing proper foundations for the buildings, and for engines and boilers, and other heavy machinery that cannot be placed on the floor of the building; also to the design and erection of a suitable chimney. Then of course questions of water supply and of drainage arise.

All these are engineering questions, and he will meet a number of others when he proceeds to carry the wires through the streets to the points where the light is to be furnished. If they are to be strung overhead on poles, the strength of the cables, the strength of the posts, etc., are important things to be considered. If they are to go underground, other engineering questions arise, such as the proper protection of the cables from moisture, etc., the means of running out branches from the mains, and other related problems.

Now, in the power station of an electric railroad, we have just such problems as the above, besides questions that arise in connection with the permanent way and the rolling stock; also, if the company intends to make its own machinery, in whole or in part, suitable shops must be built and equipped, such as boiler shops, etc.

I shall not attempt to give a description of such a power station, but will pass on to give as an illustration a summary statement of the different kinds of machinery manufactured by the General Electric Company.

Practically, these works might be said to manufacture machinery for electric power transmission and for electric lighting, but on close examination we find that these two divisions include a very large variety of machinery and apparatus. Thus, the first involves the making of dynamos,

railway motors, tramway motors, mining locomotives, electric locomotives, snow-sweepers, trolleys, motors for stamp mills, mine hoists, elevators, air compressors, rock drills, mine pumps, blowers, cranes, rock-breakers, coal-cutters, coal-drills, etc., and, in addition, all the accessory electrical apparatus, including switchboards, voltmeters, ammeters, rheostats, resistance coils, etc.

Furthermore, the various systems of electric lighting—arc, direct incandescent and alternating incandescent lighting, involve the making of dynamos of the kinds suitable for each, switchboards, regulators, lamps, lamp fixtures and a great variety of apparatus necessary in connection therewith.

Now, from what has been said, it is plain, I think, that much engineering work must be carried on in connection with the use of this machinery, but I will pass to a consideration of the factory itself, where these things are made, and, without attempting to give any adequate description of it, I will call attention to a few of its engineering features.

It comprises a large workshop for manufacturing machinery varying in size from a huge and heavy dynamo and motor, to the minute pieces that form the parts of a voltmeter or of an ammeter. Hence we have practically the same engineering features and problems that would be found in every large machine shop fitted with such a variety of tools as to be able to perform both heavy work and very light work, with the difference that in this case we find, in addition, special arrangements for doing the work that is peculiarly electrical, as the testing of the different parts of the machines, and of the entire machines by means of delicate electrical measuring instruments.

Now I have often enough detailed in one connection or another the engineering features that enter into the design and erection of any such plant, and I shall only say that there is opportunity here, which is taken advantage of, to use electric means of power transmission, and hence to not only introduce electric cranes, but also to drive a number of the individual machines by electric motors. This is a feature which is not peculiar to these works, for electric cranes are

in general use in foundries, machine shops, etc., and the electric motor for the transmission of power, is coming into general use.

These works are building some large electric locomotives, making not merely the motors, but every part of the machines; while, by way of contrast, their lamp factory affords an instructive example of a well-organized shop for turning out small and delicate work. Finally, an important part of this great establishment is the very large draughting department, with a carefully arranged system by which drawings and blue-prints are kept so as to be readily accessible for reference.

Without dwelling longer on this and similar illustrations, I will say a few words about the telephone, a subject which most of my hearers will doubtless think is very remote from engineering; nevertheless we will find in connection with it a large amount of engineering work.

The wires have to be carried from the central exchange station to the points where the subscribers are situated; and they must be placed either overhead, underground, or sometimes under water. When they run overhead there are to be considered the strength of the poles, the manner of setting them firmly in the ground to enable them to resist any load they are liable to have brought upon them, and of strengthening them when necessary by guy ropes; the strength of the cable and the tension upon it, and the strength of the cross-pieces which carry the cables.

Now, when the installation is to be underground, the cables radiating from the exchange must be suitably arranged, so that any one of them can be taken out independently of any others. This arrangement involves very careful engineering. Then comes the consideration of how the cables shall be protected underground, how they should be arranged so that each one may be drawn out at any manhole in the street just as at the exchange, how to avoid gas pipes, water pipes, etc.

If the cable goes under water it must be covered like a submarine cable, and then sunk to the bottom as is done with telegraph cables. This becomes a little difficult some-

times when the tide and current interfere with laying it in the desired position.

The exchange building should be designed specially for its intended purpose, and should be made strong enough to stand the heaviest loads to which it can ever be subjected. One of the most complicated problems to solve is how to introduce cables from the street and carry them to some central point in the building without interference.

These illustrations will suffice to show that one who is not an engineer cannot be an electrical engineer, and that the greater portion of the work of the electrical engineer is such as to require a knowledge of other branches of engineering.

As our next illustration we will take refrigerating machines, their manufacture and operation in making artificial ice, but more especially in cooling rooms, the latter finding its chief application in cold storage; an industry of very recent growth, but one which is of the greatest importance both on sea and on land, and which is rapidly growing.

For a number of years ice has been made in warm countries by means of absorption machines. In these, a concentrated solution of ammonia contained in a vessel, called the generator, is heated, and the ammonia, thus distilled off, passes through a condenser, where its heat is abstracted from it, but where it remains under a considerable pressure. It is then allowed to expand into a coil arranged in a tank of brine, which is cooled by it to a temperature below the freezing point of water. The ammonia absorbs the heat of the brine, and is then itself absorbed by a weak solution of ammonia contained in a vessel called an absorber, with which the coil communicates. The solution of ammonia in the absorber, when it has become more concentrated, is pumped into the generator, and the process goes on continuously. Then the cans of water are placed in the chilled brine, by contact with which their contents are frozen; or, if the object is refrigeration and not ice-making, the chilled brine is pumped through a coil which passes through the room to be cooled.

Such a method as this is inefficient, and is not suitable

for work on a large scale. Hence, until a better one was discovered and its success fully demonstrated in practice, no great development was possible for refrigerating machines.

The modern refrigerating machine is a compression machine, which is arranged as follows: A steam engine drives a compressor, which receives the ammonia in the form of vapor from the other end of the system and compresses it, heating it, of course, at the same time. The compressed ammonia passes into the condenser, consisting of a coil of pipe, on the outside of which water trickles, carrying off the heat from the ammonia and liquefying it. From here the liquid ammonia passes into a separator where the ammonia settles to the bottom, and the oil taken up in its passage through the system rises to the surface, and is drawn off whenever it is deemed desirable. From here the liquid ammonia passes through a valve and expands into a coil of pipe, which passes through the brine in the brine tank, and here the brine is cooled, its heat being expended in the re-evaporation of the ammonia, which is then led back to the compressor while the brine is pumped through the coils in the rooms to be cooled, or placed in contact with the cans containing the water to be frozen.

Such machines require for their development and successful construction, a careful application of the laws of thermodynamics. For ice-making, they have become absolutely necessary in warm climates, and are used to a considerable extent also in cold ones. For cold storage they are needed everywhere. Cold storage necessarily demands a structure, in which, even in the hottest weather, a series of rooms are kept so cool that meat, eggs, vegetables, etc., stored therein will be preserved from decay. By the use of cold storage on shipboard, meat can be sent across the ocean, and the benefits conferred by it on land are so evident as hardly to need enumeration. Fruits, for example, gathered at the proper season, may thus be kept in good condition for a long time, and brought to market when such products are entirely out of season; and meats, eggs, etc., may be kept fresh for a long time.

The building of the Quincy Market cold-storage plant in

Boston is on piles. The outer walls are double, having between them an air-space, which is packed with shavings. The inner walls are packed in the same way. The building is located near the harbor, so that cold water from the dock can be pumped up for use in the condensers. The building had to be adapted to: (1) the storage; (2) the plant; (3) the conveyance of the brine. In arranging the building for the storage, it was necessary to provide a suitable number of rooms to accommodate the different classes of food products, and these rooms required to be insulated from their surroundings, so that the temperature of each one could be kept at the desired point, independently of the others.

There are two engines, each running a compressor. The water for cooling the ammonia in the condenser is pumped up from the dock, and, after performing this duty, is returned to the dock by gravity.

The brine tank contains 4,500 gallons, and has a capacity of 250 tons, only 100 of which are at present utilized; but the intention is to put in a new compound engine of larger capacity (about 150 horse-power, I think) as soon as business warrants it. The usual method of refrigeration is by means of a coil of brine pipe placed around the inside of the room. At the Quincy Market, however, an indirect system is used for some of the rooms, the air being drawn by a fan over a coil of cooling pipes erected at one place in the room.

Electric lighting is used throughout the building. A machine shop and piper's shop are being added. The tank room is, of course, well protected from heat by thoroughly packing the walls, roof and floors.

If you should walk through the building and look into the different rooms, you would find them filled with all sorts of perishable materials in a good state of preservation. You would find pears, peaches and all sorts of fruit and vegetables stored here to be kept for a later market. Elsewhere you would find poultry and other meats in a frozen condition. You would observe also that the temperature of each room is regulated to a nicety, according to the requirements of the products stored, or intended to be stored, in it.

Doubtless, the largest establishment in this country for the manufacture of refrigerating machinery is that of the De la Vergne Company, of New York. The special features of the refrigerating machine which this firm manufactures are that oil is introduced with the ammonia into the compressor cylinder, partly for lubrication, partly for the sake of preventing leakage, partly for decreasing the clearance space, and partly to absorb a portion of the heat developed during the compression. Besides these there are also certain special features of construction, some of which are intended to decrease the number of joints that have to be made up, and thus to decrease the leakage.

The works are very extensive, including three large main buildings, and a fourth building, which contains a blacksmith shop and a pipe shop.

These works are quite modern and have, of course, the general features of a modern plant for the manufacture of machinery. An erecting shop has lately been added, and here every attention has been paid to securing light and to convenience of handling materials, and every separate machine is run by its own special electric motor. This avoids the use of shafting, with its pulleys and belts.

Turning our attention next to those industries in which chemistry plays the leading part, we enter the field of the chemical engineer. We will take up only two of his specialties, viz.: the refining of sugar, and the manufacture of paper.

*Sugar Refining.*—I will begin by outlining briefly the process that must be followed, without attempting much detail; and in doing so, I will have in mind the routine of operations practiced in the Standard Sugar Refinery, at South Boston.

The raw sugar is received at the refinery in bags or sacks, from which it is emptied into the melting kettles. These are large, covered, cylindrical chambers built of brick and cement, and provided with a number of coils of perforated steam-pipes. Steam is now let on. This melts, and of course, dilutes the sugar. The resulting liquid, containing about fifty per cent. of sugar, is now pumped to the blow-

ups, which are large tanks, situated higher up in the building. Into these tanks, air is blown for the purpose of keeping the liquid in a state of agitation and consequently thoroughly mixed. This counteracts the tendency of the liquid to local solidification, and at the same time reduces its temperature. A little lime is here introduced to neutralize the acidity, if there be any.

From the blow-ups, the liquid flows by gravity to the filter-pans. These are flat, shallow pans with series of holes in the bottom, and below each hole is a nipple to which is attached a bag filter. This consists of a large bag of coarse material, confined within a smaller bag to keep the large one from being distended, and failing to perform its functions. The liquid is now filtered through these bags, and the syrup passing through them is then ready to be taken to the charcoal filters.

When the bags have become so choked up with dirt as not to filter well, they are detached from the filter-pans, and the adhering material is emptied out, and taken to a filter-press. The syrup here squeezed out is taken to the melting kettles, while the residue, which is only dirt, is thrown away. The bags are then washed by passing them through running water and wrung out between rollers. The water in which the bags are washed is then sent back to the melting-kettle.

The bags are now in condition to be used again by placing the large bag inside of the small one as before. This was done with more or less difficulty by hand, until a simple machine was devised, in which automatic fingers, attached to a piston moving in an upright tube, drew the bag into the tube with the aid of a partial vacuum. The large bag is then dropped into the sheath or outer bag, the rapidity of the drop being regulated by the amount of air admitted behind the piston.

The syrup that has passed through the bags is transferred by a pump to the bone-charcoal filters. These are 20 feet deep and 12 feet in diameter. The syrup is thus decolorized, and it then goes to the vacuum pans, where the water is boiled off, and the sugar is formed. The sugar is

then dropped into a conveyor, where it is made to travel along by a screw and delivered to the centrifugal machines. The water is here driven out, and the sugar is left white, and very nearly dry.

Next it is granulated. For this purpose it is introduced into the upper end of a long cylinder inclined a little to the horizontal, and the rotation of this cylinder alternately raises it and lets it fall, at the same time feeding it slowly forward to the lower end, while a series of hammers constantly jar the cylinder so that the sugar shall not stick to the sides. In this way the sugar is dried. On leaving this cylinder it is carried on a belt-carrier to the bin where it is stored. As with grain in a grain elevator, no attempt is made to keep separate the sugars made from the different lots of raw sugar.

Such, in brief, is the process through which the sugar is carried, but the bone-black must undergo a process also. When the syrup has filtered through the bone-black for a certain length of time, the latter is found to be dirty, and has to be cleaned. For this purpose the filters are opened near the bottom, and the bone-black is drawn out with a rake, and conducted into vertical retorts where it is heated to redness, and the dirt is thus burned off. The bone-black is then allowed to cool to a certain extent before the retorts are opened, and after it has cooled down further it is returned to the filters. The final cooling is accomplished by running the bone-black into a kettle provided with pipes through which cold water circulates. Under the retort is a fire which heats the bone-black to a temperature of about  $700^{\circ}$ , and it is left at this temperature for several hours. Now, as it cannot be exposed to the air at once, it is passed into sheet iron flues, and allowed to stay there until it cools to a temperature of  $400^{\circ}$ . From here it is transferred to a hopper, and this transference must be done at a regular rate and in measured quantities. This is accomplished by some very ingenious special machinery. From the hopper the bone-black is dropped upon a belt-carrier, which takes it to the kettle already referred to. From this it is taken by another belt-carrier, provided with little buckets, and

carried to the room where the tops of the filters are situated, and, finally, a horizontal belt-carrier delivers it to the filters.

The above is a very brief description of the various processes that have to be carried out, and a successful performance of the work demands the greatest care and nicety of operation at all points, especially in properly sorting the different qualities of the syrups that come from the bone-filters, and in operating the vacuum pans.

Of course, the superintendent must look carefully after these matters, and chemical analyses have to be constantly made, since the least carelessness in carrying out the process may result in very serious loss to the company. Nevertheless, the process and the greater part of the chemical work become in time largely a matter of routine.

When, however, we undertake to carry out any such complicated series of processes we have to use a large amount of machinery, and extensive buildings of sufficient strength and stability have to be built.

It is frequently necessary to build wharves or quays to receive the vessels that bring the raw sugar; and to erect buildings which must provide space and facilities for storing the raw and refined sugar, and hence must sustain heavy loads. Then the portions of the building where the various parts of the process are to be carried on must be so designed as to be most conducive to economical handling. Then there is considerable opportunity for devising special machinery and special arrangements to accomplish special objects. Thus, the syrups are usually transported from one place to another by pumping, and part of this pumping is done before it has been passed through the bag filters. All this means that we must have pumps that can raise a thick liquid, and which will not become clogged with dirt that comes from the melting kettle. Then, for transporting the sugar from place to place, and also for transporting the bone-black, belt-carriers are used, *i. e.*, endless rubber belts. In the refinery which is now being built at Greenpoint, L. I., which is the largest single refinery belonging to the Trust, and in which the greatest care is being taken to in-

troduce the most modern and approved methods and machinery, the coal is received at a long distance from the boilers and is carried to them on belt-carriers.

Another labor-saving device is the mechanism already referred to, for sheathing the filter bags. Another is the machinery for delivering the bone-charcoal at a known uniform rate, from the sheet-iron flues to the hopper. Then there is machinery for packing, and for lifting barrels, etc. The special sugar machinery likewise (such as centrifugal machines, vacuum pans, etc.,) must be very carefully made and requires nice engineering skill in its design and construction. Besides this, a large amount of very nice engineering work must be done in connection with the evaporation in the vacuum pans, which are sometimes run with triple effect, the three evaporations being carried on successively, the steam for one being furnished by the evaporation in the next preceding one. Then of course there are the boilers, the engine or engines, the chimneys, etc. Evidently, therefore, a very great amount of engineering work must be done in order to make the plant a success.

As another illustration let us take the manufacture of paper from wood pulp, for which purpose I will give a brief description of the processes carried on at the works of the Russell Paper Company at Lawrence, Mass. The kinds of wood used are poplar and spruce. The wood is cut into chips, and these are mixed with a liquor which attacks all the ingredients of the wood except the cellulose. This liquor is put, with the chips, into a boiler or digester, into which steam is introduced and in which the mixture is cooked for a suitable length of time. The mixture is then drawn off and washed, and the water and impurities are thrown away, and pure cellulose is left. This, mixed with water, constitutes the pulp. To make a satisfactory product, two different kinds of pulp, sulphite pulp and soda pulp are used, which are mixed in proper proportions, viz.: the sulphite pulp alone would make too harsh a paper, while soda pulp alone would make too weak a paper. The first is used to give strength to the product, and the second softness and delicacy. The sulphite pulp is made by treating

the chips with an aqueous solution of sulphite of lime, the chips, liquor and steam being mixed in a spherical boiler which is kept rotating during the cooking. The soda pulp, on the other hand, is made by boiling the chips in a solution of hydrate of soda, and, instead of using a rotating boiler, the chips and the liquor are placed in a vertical cylindrical vessel called a digester. This vessel is provided with a perforated plate near the bottom, and on this plate are placed the chips. The steam is then introduced below the plate, and the liquor is caused to circulate through the chips, during the cooking operation.

In both cases, after the cooking operations are completed the pulp is pumped up to a beating machine, where it is thoroughly mixed, and the fibres are drawn out by causing them to pass between revolving beaters. Here it is also more thoroughly washed than it was after leaving the boilers or digesters.

In the case of the soda pulp it is sometimes bleached in the troughs in which the washing and heating is done.

After the pulp leaves these troughs it is made to pass through a series of very fine screens of metal plates having a series of thin slats. Thence it goes to the wet machine, which is a trough through which a continuous flannel roll is made to pass. The pulp adheres to the flannel and the water drops off. Then the flannel, with its layer of pulp, is squeezed between several sets of rollers from which the pulp layer emerges as a kind of thick paper, but destitute of consistency. Then, if it has not been previously bleached, it is conveyed on trucks to the bleaching pots. In these it is placed, together with the bleaching liquid, and the whole is stirred by agitators. From here, when the bleaching is finished, the pulp is conducted to a room with a perforated floor, where it is washed by a stream of water from a hose, leaving the bleached pulp on top of the false floor.

Next follows the mixing operation. In the trough of the mixing machine are placed the sulphite and soda pulp in the desired proportions, together with any other ingredients that may be desired, such as clay to make the paper take

ink, sizing, resin soap, etc. By suitable machinery the materials are caused to travel round and round in this tank until they are thoroughly mixed. For the finer papers a Jordan engine is used instead.

After this the pulp is ready for the paper machine proper, which may be a Fourdrinier or a cylinder machine. In either case, the pulp is caused to adhere to a layer of cotton or wool, which forms, as it were, an endless belt, the water dropping off, and the pulp being carried along on this cloth, gradually passes between pairs of rolls, the first pair usually making the water mark. The pulp then reaches the calender rolls, inside of which steam circulates. Here the pulp is dried, and, as it were, ironed, and receives a gloss. It is then rolled and subsequently cut into sheets of any desired size.

The foregoing is a very brief description of the principal steps only. The following important details have still to be mentioned:

(1) When the wood is received at the mill, the bark and any other roughness are removed by a special machine, made somewhat on the principle of a milling machine. Any large knots are then drilled out, a machine being also provided for this purpose. The log is then placed in a machine containing a set of revolving knives which chips off the wood obliquely to the grain. From this machine the chips are carried by belt-carriers to the upper part of the building, where they are led to hoppers over the boilers or digesters respectively.

(2) The sulphite of lime solution is made as follows. On an upper floor are three closed tanks, arranged on three different levels and so connected that a liquid in the upper one, when it reaches a given level, will overflow into the second one, and in like manner from the second into the third. When it reaches a given level in the lowest tank it overflows into an open tank placed at a still lower level, and directly over the boilers. Above the system of three closed tanks is another open tank containing lime water, which flows continuously from this tank downwards through the entire system. In the basement is a furnace for burning

sulphur, and thus forming sulphur dioxide, and the passage through which this gas escapes from the furnace leads into the lowest of the system of three tanks, then into the next and then into the upper one, from which it is pumped out by a vacuum pump, which draws the sulphur dioxide and the accompanying nitrogen through the solution in the three closed tanks. The sulphite of lime thus formed overflows into the lower open tank, from which it is delivered by means of a hose to the boilers.

(3) The hydrate of soda is made by boiling soda ash and lime water by means of a current of steam passing through a coil of perforated pipes within the boiler. The hydrate of soda is drawn off, and the carbonate of lime is thrown away.

(4) The material washed out from the pulp in the soda process is, of course, very dilute, but it is nevertheless, desirable to reclaim and to re-employ the soda. For this purpose the liquid is reduced in a Yaryan evaporator to the consistency of molasses, after which it is placed in a revolving drum, open at both ends, one end communicating with a furnace, and the other with the chimney. The inside of this revolving drum is conical. The material is thus burned, and comes out as a black ash, consisting of soda ash, carbon ash and a little sand. This black ash is leached with water, which dissolves out the soda ash, leaving behind the other ingredients, and we thus have again a solution of soda ash from which to make the liquor.

Here again we have buildings, tanks, furnaces and other constructions to erect, and a very large amount of machinery to operate and keep in repair, even if we do not have to design and build it.

I have cited, in these three lectures, a number of examples of industries where the work of the engineer is required, and, although these are only a few examples selected from an almost countless number, they will, nevertheless, show us much better than can any definition that can be framed what is the range and what the character of the work of the engineer.

Whenever a structure is to be erected, be it a bridge, a breakwater, a furnace, a tank, or a building, or be it what it

may, in order that it should answer its intended purpose it must be erected in accordance with correct engineering principles; and the same is of course true of machinery. Regard must be had to its strength, to its stiffness, and to the efficiency and economy with which it can perform its functions.

Having discussed the nature and the range of the work of the engineer, we are now prepared to consider what kind of an education should be given to a young man who is to make engineering his life work, and this I shall proceed to discuss in the next lecture.

It is no longer necessary to undertake to answer the arguments of those who take the ground that a proper mental training, and hence, a proper education, is only to be attained through the pursuit of classical and literary studies; and that the tendency of a course of study which deals with science and the applications of science to the industrial work of the world, is to exercise a narrowing rather than a broadening influence upon the student, unless it be preceded or accompanied by a classical and literary course.

This matter has been the subject of a vast amount of discussion, especially among professional educators, and among those who devote a good deal of time and thought to a study of different systems of education and their effects, particularly as regards the mental development of the pupil.

It is now generally, if not universally, admitted that, not only can a good mental training be attained by a variety of different courses of study, but also that in order to give to any individual the best mental training possible for him, and hence the best education, the course which he should pursue should depend upon what is variously termed his natural aptitude, his bent, or what he has a taste for; and that if the course of study which he is made to pursue is a different one, his mental training, and hence his education, will be more or less successful in proportion as it is less or more removed from the course which is suited to his natural aptitude.

It is the stage of educational progress marked by the evolution of this idea that has caused our colleges and uni-

versities to do away with one fixed curriculum, and to introduce the elective system, *i. e.*, a system of elective studies or elective courses; and so completely has this degree of progress been attained, that the number of colleges that still adhere to one fixed curriculum is very small.

The next stage of educational progress is marked by the evolution of the idea that scientific study, and the study of science as applied to the industrial work of the world, is fully capable of giving the very best mental development to those whose aptitude lies in that direction; and this idea is now very generally conceded, although it had to have a hard fight to gain its position, and there are still a few remaining who oppose it.

The degree of success achieved by the advocates of the new education may best be judged by the enormous development which has taken place in the last twenty or twenty-five years in the scientific and technological schools of the country. Not only has the number of such schools increased very largely, but the increase in the number of pupils in these schools also has been phenomenal. It is thus conclusively proved that there is a very large and rapidly increasing number of persons who choose to give their sons such an education as these schools have to offer, rather than such an education as is offered by the colleges, and who believe that they are thus giving them a better equipment to meet and deal with the problems of life, under whatever circumstances they may be thrown.

But even more evidence is furnished of the prevalence of the idea by contrasting the character of the courses of study offered, and the equipment of these schools to-day, and their condition in these respects about twenty years ago.

It will be evident to any one who will institute such a comparison, even superficially, that the entire drift of the development of these schools has been in the direction of making them more thoroughly scientific, more thoroughly practical, and more closely in touch with the live questions of the industrial work of the day, and the industrial outlook for the future.

In other words, they tend more and more to concentrate

the attention and thought of the student upon those subjects that will fit him best for his life-work, making the extent to which other subjects can be introduced dependent upon the time that can be afforded for them consistently with a thorough performance of the work that forms the main objects of the course.

This tendency is not one started by a few educators, which may be lightly charged with lack of wisdom. It is one which has been irresistibly forced upon the schools by the spirit of the age, and which is in the direct line of progress, and, like all other things that are in the line of progress, it cannot be stopped.

Far be it from me to undervalue a thorough classical or literary education, for those whose natural aptitude lies in that direction, or to dispute the desirability, nay, importance, of giving to the engineering or technical student a certain amount of literary training; but I believe that the foremost and principal object to be accomplished by any system of education is mental training, *i.e.*, the development of the powers of the mind, and that this is far better attained by doing some one line of work thoroughly, than by scattering one's energies over a large field. There is no more effective means of imparting to the young man powers of mental concentration, and of fitting his mind to grasp and grapple with the serious work of life, than a course of scientific and practical study. The acquisition of this mental power is the principal object of education, and, if this be neglected, the result is shallowness and not education, even though the student may have done more or less reading, and acquired more or less information on a variety of subjects.

If mental training has been neglected in the education of a young man, it is only with the greatest difficulty that he can repair the damage, and acquire mental power later in life, and, moreover, a greater amount of varied information will not compensate for, nor take the place of, the disciplined power of the mind; whereas, if this has been acquired even by the sacrifice of a certain amount of general reading and information, it is far easier to do this reading later.

Hence, when an engineering course is to be laid out, it should be planned as an engineering course, and should aim to accomplish its object of fitting the student to become an engineer in the best and most thorough manner, and then should be added such general studies as will not conflict with a thorough accomplishment of the engineering work; and the fact should be kept constantly in view that it is mainly on the scientific and practical work of the course that reliance is to be placed to impart mental training; and that, although the general studies are very important, and have their educational value, besides serving to give information, the part they play in giving mental training is far less than the part played by the scientific and practical work.

Another matter, which only of late years has received full recognition, is that the training of the hand and eye forms an important factor in all education, and especially so in a scientific and a technical one. The recognition of this fact is due primarily to the development of the study of science, and especially of applied science; for, in order to make such study successful, it is necessary that the student should observe and experiment, and thus ask questions of nature, and then understand how to interpret correctly her replies.

Thus, the performance of chemical laboratory work by the students with their own hands has been carried out for a number of years in the case of those who were fitting themselves to become chemists. The introduction of physical laboratory work, performed by the students themselves, is of much more recent date; but since its introduction it has been adopted to a very considerable extent, and has proved to be one of the best, if not the very best, means of training the student to perform experimental work with accuracy and thoroughness; to observe, note and collate the facts as they occur; to make measurements with great precision, and to understand and appreciate what are the sources of error that are inevitable, and what are the limits within which the conclusions can be assumed to be correct. The introduction of laboratory practice into the teaching of

natural history, of chemistry and of physics constitute a great advance over former methods of teaching science.

But of late years other advances which have been made have exerted a most important influence on technical, and especially on engineering education, namely, the introduction into engineering courses of study, of practice in engineering laboratories, where the student is taught to perform experimental engineering work on a large scale, and under such conditions as occur in practice, thus putting him in touch with the sort of work he is liable to be called upon to do after he enters his profession. Thus, we find, in connection with engineering schools, laboratories for testing the strength of materials, steam laboratories, hydraulic laboratories, mining laboratories, electrical engineering laboratories, chemical engineering laboratories, etc.; and, although they form a comparatively recent addition to the work of engineering schools, their number, their equipments and their efficiency have increased with surprising rapidity during the last few years, so that now there is hardly a school in the country claiming to teach engineering that does not consider it necessary to make an attempt to establish engineering laboratories of some sort.

The other development referred to is the enormous impetus that has been lately given to manual training.

It is true that in France and Germany there have been established for some time what may be called technical schools, which are in no way engineering schools, but more properly trade schools, and that the influence of these schools has been very beneficial to the manufactures of those countries. But the idea of the manual training school is not that of a trade school, but one where, in addition to some more elementary studies of a general and of a scientific nature, the student is taught the use of tools, the object being to educate his hand and eye, to train his powers of observation, to teach him to do work accurately, and to cause him to understand how materials behave by having actually handled and worked with them. And so general has the idea become of the importance of giving this kind of education to children, that not only have large and suc-

cessful manual training schools sprung up all over the country, but steps have been taken, and are constantly being taken, to give this kind of instruction in the public schools; so that it has already been introduced in many localities, and is rapidly extending.

Even England has waked up in this matter, and displays far more energy than ever before in founding science schools for younger pupils and for artisans. Now, while the product of the manual training school is not an engineer, and while a very sharp distinction should be drawn between the graduate of a manual training school and the graduate of an engineering school, nevertheless, a thorough drill in the use of tools is a matter that the engineer cannot afford to neglect. It develops in him a familiarity with the behavior of materials, which he cannot acquire as well in any other way; it gives him a knowledge of how the actual work must be done, and of what is good and what is poor work; it enables him to know how any piece of work should be carried out, and to judge whether it is satisfactory or will be so when it is finished; so that the instruction given through actual work with tools in the shop is a matter which, unless it has already been taught in the preparatory school, should receive its fair share of attention in an engineering course, although it is not the most important element. Moreover, all the recent impetus given to a proper training of the hand and eye as an important educational factor, whether it finds expression in the laboratory, in the workshop, in the manual training school, or even in the trade school, is fast removing whatever remnants of prejudice still exist which would cause hand-work to be regarded as degrading, and instead, the world is coming to the conclusion that it is necessary to a proper education, and, hence, honorable in every way, and also that an education is not complete that does not introduce hand-work at some stage.

Whereas the student of engineering of former times found the only courses open to him in the schools that tended to fit him for his profession were such as could be acquired by studying books and listening to lectures, and while he found that books of pure mathematics had been

developed to a considerable extent, he found also a great paucity of books that treated in a thoroughly scientific manner of the applications of science to the practice of the profession he desired to enter; the student of to-day finds a far larger supply of books that deal with the live questions of engineering, besides a very extensive and valuable periodical literature, and, as additional advantages, he finds workshops and laboratories of all kinds open to him, opportunities far greater than ever took shape in the wildest dreams of the engineering student of former times.

So rapid has been the increase in the facilities furnished by these laboratories since they began to exist, and so great is the rate at which their scope and material equipment is increasing, that no limit can be set beyond which their development may not carry them, and we may expect them to progress further and further, ever bringing our engineering courses more and more into touch with the live problems of the day, and reacting ever more and more upon the character of the theoretical portion of the instruction by furnishing it with an ever wider basis of experimentally ascertained and experimentally verified fact upon which to build, and thus developing greater and greater opportunities for the education of the young man; and, inasmuch as the law of nature is a constant growth and development, so must these opportunities be ever on the increase, so long as engineering work shall be required by the inhabitants of the world. The foregoing remarks furnish, in an exceedingly brief and general way, a view of the opportunities that can be taken advantage of; and, therefore, the question which presents itself to us, in view of all these possibilities, is, what is, all things considered, the best course of instruction to give a young man who is to make some kind of engineering his life work?

And, first of all, shall we make a more successful man of him by taking advantage of these opportunities, or by merely teaching him to read, write and cipher, and, perhaps, to draw a little, and then, setting him to work in the field, in the shop, or in the draughting-room, to make his own way as our grandfathers did, only rising to higher engineer-

ing functions through, and after having fulfilled a long course of practice in the lower, which course sometimes might be called apprenticeship, and sometimes had in it hardly enough of the element of instruction to deserve that name? In other words, shall we undertake to teach him first the scientific principles upon which his life work is based, and then set him to work at it, beginning, of course, at the lowest round of the ladder, or shall we leave him to gain whatever knowledge of principles he may acquire by experience and hard knocks, and only learn to avoid failures by first making them, or else by picking up slowly and laboriously, and in a disconnected way such bits of scientific knowledge as he can at odd moments, stolen from a day full of cares, of anxieties and of business? That a number of the most brilliant stars in the galaxy of the world's greatest engineers have been obliged to follow the latter course, and that in spite of it they have achieved the very highest success and renown, is not to be denied; and they deserve all the greater credit and the higher encomiums for having accomplished all that they did under such adverse circumstances; but I believe that almost, if not entirely, without exception, they would agree that the work they could have accomplished would have been even grander had they had greater educational advantages of a scientific and practical nature in youth, and that they would have saved a great deal of time and hard work if they had been taught early the experience of the past, and the scientific principles and facts of nature so far as they were known at the time, instead of having to steal time from their all-absorbing occupations to pick them up little by little.

I am fully aware of the fact that discussion after discussion has taken place upon this subject, and argument after argument has been advanced both for and against each of these methods of preparing a young man to take up the profession of engineering. To undertake an enumeration of all the discussions that have been held, or of all the arguments that have been put forward, would be an endless task, and I shall not weary you with any such attempt.

It is true that a great many of these arguments are

wholly irrational and unworthy of consideration. But we should be careful, in considering them, to do so in a judicial spirit, and not to stamp as wholly irrational everything that is put forward against our own views, and as wholly reasonable all arguments advanced in their favor.

What we ought rather to do, is to begin by separating and laying on one side all the arguments that are wholly absurd and irrational and unworthy of consideration, and then to take up and weigh carefully those advanced by persons who are capable of serious thought, and who have such experience or knowledge of the facts as entitle them to have an opinion on the subject, and who have, therefore, some real or imagined reason, or some partial reason for the arguments which they advance.

Devoting our attention to these, we should endeavor to put ourselves into such a frame of mind that we can realize and understand what are the facts upon which their authors base their conclusions, and to appreciate the point of view from which they look at these facts, real or supposed; and then we shall be better able to pass judicial judgment upon the questions whether their assumed facts really exist, whether they are such as existed at one time and have ceased to exist now, and whether their conclusions are correctly drawn from their observed facts.

That there have been many, and are still a few, men of experience, and of at least fair intelligence, who have taken ground against an education in a scientific school as a preparation for an engineering profession, is a fact not to be denied; but it is also a fact that any such opposition on the part of the experienced and intelligent portion of the community is far less to-day than it formerly was, and what little opposition there is left is fast disappearing, and changing to hearty approval.

In trying to analyze the discussions and arguments against engineering education, we may attempt a certain crude classification, as follows:

(1) There are those who proceed from ignorance and prejudice, and the phases of this ignorance and this prejudice are so varied that it is only possible to enumerate a few.

(a) There is always a good deal of talk about the dignity of labor, and it is true that, in the older state of society, labor was thought to degrade a man, but the reaction from this false position has led to the view taken by some ignorant people that any occupation which involves the use of a man's brain, whether accompanied or not by the use of his hands, is degrading. The difficulty with these people is that they do not understand that manual labor is not by any means the only kind, nor is it the hardest kind of labor; neither do they understand that unskilled or unintelligent manual labor is of far less value in doing the work of the world than manual labor performed with intelligence.

(b) There is the stupidity and obstinacy of the man who, having become accustomed to one way of doing a thing, is ready to oppose any scheme or proposition which is liable to lead to the conclusion that some other way may be found better than his, and who is especially opposed to any innovation if proposed by some one who has reasoned it out by the use of scientific principles which the former does not possess.

To this class belong a good many who oppose the use of new and improved machinery. It is needless to say that, inasmuch as the world always progresses, such a position as the above injures most the one who holds it.

(c) There is another class who systematically oppose the introduction of labor-saving devices, on the ground that the introduction will diminish the work to be done, and, therefore throw a number of people out of employment. They do not realize that the final result is to provide more time for the workers to accomplish a larger amount in the way of results by their labor; for it is a fact that, as labor-saving machinery has been introduced, the comforts and convenience of the entire community have increased, and the very objectors would be unwilling to put up with only such comforts as were available in olden times when no labor-saving machinery had been introduced.

(2) A certain number look to the past, and because there have been men who, with imperfect means at their command, have achieved success and renown, they believe that

the course most conducive to success is to imitate them in all external particulars; and that because they accomplished what they did with little early education, therefore, the young men of to-day will succeed best by having no better education.

They do not realize :

(a) that their success was accomplished in spite of difficulties and in the absence of early advantages, and not because of them; and that their spirit of indomitable energy caused them to conquer the difficulties with which they were surrounded, and to utilize to the fullest extent all the advantages that they possessed; and that the same indomitable energy would have led them to utilize to the fullest extent a greater number of advantages had they possessed them.

(b) that the world is ever progressing, and that, therefore, the new conditions that arise in consequence of this progress present ever new problems to the engineer to solve, which require a knowledge of the experience of the past, and that the more of this experience, in other words, the more science, the young man is already familiar with, the better will he be prepared to meet and grapple with them.

(3) As a rule, an engineer who has started in life without an engineering education, especially if he has had a fair degree of success, realizes the importance of such an education, knows that he could have accomplished more if he had had it, and desires that the younger generation should have better advantages, and be better equipped for their start in life than he was for his, knowing that if the sons were not to make more progress than their fathers, the advance of civilization would soon be at an end. Nevertheless, every now and then we find some engineer, usually one who is not very able, who values so highly his own accomplishments that he is willing to set them up as a standard for future generations; and knowing that he has reached this standard, although he had no engineering education, he therefore concludes that neither should they have such an education.

It is unnecessary to say any more to show the utter fallacy of the objections stated above; and when we omit a consideration of these, and proceed to analyze the rest of the arguments that have been advanced, I think we shall find, if we read them carefully, that, as a rule, their authors do not object to an engineering education, and, indeed, deem it very necessary and desirable; but they intend their objections to apply to some specific kind of education, the details of which they deem ill-advised or unsuitable. Indeed, I recently undertook to analyze carefully a long discussion of this sort, in which the author made such a number of careless and even contradictory remarks, that to any one who read only certain of his articles it would appear that he did not believe at all in an engineering education. But I found that, after all, he did express himself elsewhere as fully approving such an education and emphasized its importance, and interpreted what he had said that appeared to contradict this idea as meaning simply an objection to certain features of such a course as he imagined was carried on in some places.

Moreover, we should remember that engineering schools are of comparatively recent growth, and that they have been constantly improving their courses, adapting them more and more to the needs of the student who is to enter the engineering profession, so that the courses given in these schools to-day are far different from those given twenty years ago, when engineering schools were still in their infancy.

Having disposed of the objections to such a course, it seems hardly necessary to present many more arguments than those already advanced in its favor. So much progress has been made in engineering science, and so great have been the developments and improvements in the ways of doing work, that when an engineer undertakes work of any considerable importance, he is obliged, in order to accomplish it properly, to make use of so many kinds of engineering—and hence to be familiar with the scientific principles governing them—that it has become practically an absolute necessity that if a young man is to enter the engi-

neering profession with any chance of ultimate success, he should start with an engineering education already acquired.

The importance of such an education has been urged over and over again by a host of the most prominent engineers, and in the most positive terms. As an example, I may cite the address made by Sir John Fowler, before the British Institution of Civil Engineers, upon assuming the presidency of that institution in 1866. This address was devoted entirely to the education of the engineer, and it was deemed of so great value and importance that it was reprinted and very widely circulated.

I will quote a few remarks taken here and there from that address. He enumerates some of the most important engineering works which were being carried out or planned at that time, and he says:

"All these works present problems of great interest, and it will require cultivated intelligence, patient investigation, and enlarged experience, to accomplish the task of their satisfactory solution;" and again: "In the solution of these problems, thus rapidly indicated, and in others which could easily be adduced, we may rest perfectly satisfied that the difficulties they present are not to be overcome by a stroke of genius, or by a sudden happy thought, but they must be worked out patiently by the combination of true engineering principles, ripe experience, and sound judgment."

And, later on, just before he presents his idea of the kind of course he would prescribe, he says:

"We, of the passing generation, have had to acquire our professional knowledge as best we could, often not until it was wanted for immediate use, generally in haste and precariously, and merely to fulfil the purpose of the hour; and, therefore it is, that we earnestly desire for the rising generation those better opportunities and that more systematic training for which in our time no provision had been made, because it was not then so imperatively required."

But the best evidence of the necessity of such an education is the great demand which exists for the services of the graduates of engineering schools to-day. In our own

case, *i. e.*, that of the Massachusetts Institute of Technology, notwithstanding the fact that the increase in the numbers of our students during the last few years has been phenomenal, the number of our graduates from year to year does not begin to keep pace with the demand for them, and the heads of the engineering departments are constantly in receipt of a much larger number of requests for them than can be supplied. Also, those who carry on industrial establishments in this country find that it pays them best to have as assistants young men who understand scientific principles, and who are consequently able to take a certain amount of responsibility, and who, therefore, can grapple with an emergency; for, in a live industrial business, emergencies are constantly arising, which can only be met by clear judgment and a knowledge of scientific principles, and the heads of these establishments have less and less use for men who are merely drilled in performing one operation, and know only that; so that this latter class of men are less and less in demand in this country.

In England, the above-stated condition of things is not yet realized, but the facilities for an engineering education are increasing, and there is a constantly increasing sentiment in favor of it. Moreover, the influences at work are such as cannot fail to bring about, before a very great while, the same condition of things as exists now in America.

The next matter for consideration is the nature of the course of study that should be pursued by the prospective engineer. In the preceding lectures I have enumerated and described a variety of engineering industries and of establishments where engineering formed at least a large part, and often the greater part, of the work to be done. The cases cited furnish examples of a number of kinds of engineering, commonly defined by the qualifying words civil, mechanical, mining, metallurgical, electrical and chemical, and perhaps some other industrial operations which are not usually classed with engineering.

If we analyze carefully the work to be done in all of them, we shall find that in many, and I might almost say in

all, there are, first, certain processes to be carried out in order to manufacture the desired products, as, for instance, the various processes of melting, filtering, decolorizing, drying and granulating, through which sugar must be carried in a sugar refinery; the series of chemical processes to be pursued in making soaps or glycerine; the metallurgical processes necessary in the manufacture of steel—the proper mixtures of ores, fuel and flux, the proper furnace treatment, etc. Second, we shall find that attention must be given to devising and preparing the means for carrying on these processes efficiently and cheaply; such as designing and building suitable furnaces, machinery, etc.; not solely for the purpose of carrying on the process, but also for a proper and economical handling, so that as little labor as possible may be necessary in receiving the raw materials at the works, in transporting that which has just completed one process to the place where it is to undergo the next, and in getting the finished product out of the works to the consumer or to the market.

This matter of economical handling is one of the most important items about a manufactory, and involves a careful consideration of the proper arrangement of the machinery in the works.

Then arise the questions respecting the best kinds of machinery to use for all the steps in the process, including a consideration of its efficiency, durability, first cost, the expenses necessary for attendance, also for its maintenance and repair; the expenses necessary for labor in the performance of the several processes, including the labor of handling, of loading and unloading, of transporting, etc.

Next comes the consideration of the nature, construction and arrangement of the power plant, whether water or steam power, or both, are to be used. If the former, the proper constructions, such as dams, canals, locks, etc., to bring the water to the wheels, and to discharge it when it leaves them, proper wheel-house, and selection of wheels.

If steam is to be used, the choice of the kind of engine, whether there shall be one or more, and where it or they shall be located, depend upon the character of the work to be done and the uses for steam in the works.

All these matters must be carefully considered with a view to efficiency and economy in the long run. The selection of boilers, the erection of chimneys, boiler-house, engine-house, etc., are all important questions.

Then comes the construction and arrangement of the whole power plant; and next, a consideration of the proper system of transmitting the power from the various sources of power to the different points in the works where it is to be used, whether by shafting, gearing, belting, cotton or manilla ropes, wire ropes or electric dynamos and motors.

Then we shall have to determine the proper design and construction of buildings adapted for the work, including proper foundations for them, proper water supply, proper drainage, proper heating and ventilation, proper light in daytime and when daylight is either not available or not available in sufficient quantity, fire protection, as well as a large number of questions of a similar character, all of which are generally recognized as engineering questions, and of which it would be almost impossible to give a complete list.

In the infancy of manufactures the processes are liable to be the all-absorbing problems, *i. e.*, by what processes to produce the required result; but as any one of these manufacturing interests develops, the processes become more or less a settled thing, or, at most, the opportunities for variation from one fixed method are few, and all manufacturers have to conform more or less closely to this fixed method.

When this state of things is reached, the manufacturer who would succeed is forced to pay attention to the engineering problems that arise in his business; and a failure to solve these problems satisfactorily results in very serious loss to the concern, and may more than eat up all the profits.

If, in view of all the above, we were to attempt to define the different kinds of engineering previously referred to, viz.: civil, mechanical, mining, metallurgical, electrical and chemical engineering, and to designate certain kinds of engineering work as belonging to one or the other of these

professions exclusively, we should find that, after all, there is no dividing line between them and that much of the work is common to all of them. Hence, these distinctions, so far as they refer to a classification of engineering work, are purely artificial. Moreover, a man cannot be a successful mining engineer, a successful metallurgical engineer, a successful electrical engineer, or a successful chemical engineer, unless he is an engineer well versed in the science and practice of engineering.

We might then define the mining engineer as the man who performs the engineering work in any of the mining industries; the metallurgical engineer as one who performs the same duties for a metallurgical works, and so on.

The mining engineer, in order to be able to do his work properly, must be versed in the processes to be followed in mining operations, otherwise he will fail to appreciate what are the objects to be accomplished, and hence he will not properly adapt his engineering work to the required ends; and so, also, in the cases of the other kinds of engineers mentioned.

Hence, the mining, the metallurgical, the electrical, or the chemical engineer must be, primarily, an engineer, but he must also be sufficiently versed in the special mining, metallurgical, electrical or chemical processes, to be able to adapt his engineering work to their needs.

When we come to the terms civil engineering and mechanical engineering, both of which, at different times have been used in different senses, and both of which have often been used to denote the engineer as I have described him, it is impossible to draw a line, and to assert that any one set of engineering operations belongs exclusively to the civil or to the mechanical engineering profession. Indeed, the term civil engineer has been used at different times to denote all grades, from the thoroughly equipped engineer to the mere surveyor, who knows no engineering at all. Hence, it would not be worth while to attempt to give the various definitions that have been proposed for a civil and for a mechanical engineer. So various and arbitrary have been these distinctions that, according to some, the build-

ing of wooden ships belonged to the civil, and that of iron ships to the mechanical engineering profession.

According to the ideas at the present time, generally prevalent among those who make a distinction between the two, it may be said that the work of the civil engineer is associated with the design and erection of what might roughly be called public works, as roads, railroads, bridges, canals, improvements of rivers and estuaries, lighthouses, water supply, sewerage, irrigation, etc.; and that the work of the mechanical engineer is that of dealing with machinery. Hence, the person who had charge of and performed the engineering work for machine shops, for cotton mills, woollen mills, silk mills, flour mills, rolling mills, metallurgical works, manufactories of steam engines of all sorts, whether stationary, marine or locomotive, manufactories of all sorts of machinery, chemical manufactories, motive power and rolling stock departments of railroads, etc., would be called a mechanical engineer.

If, however, we should adopt these as definitions, and proceed to determine the kinds of work which each one would be liable to be called upon to perform, we should find no class of engineering problems that would not probably arise in the work of either the civil, or the mechanical engineer. To illustrate, take the case of the Forth bridge. You will remember that very large machine shops had to be planned, built and operated; that enormous amounts of machinery had to be used; that a very large portion of it was special machinery, which had to be specially designed and built, and operated under very peculiar circumstances. There were required a number of power plants, including steam engines, steam boilers, etc., all of which had to be built and operated; compressed air had to be produced and used in very large quantities; electric light plants had to be established and operated; a large number of cranes had to be built and operated by power; and an enormous amount of engineering work had to be performed, which, if one attempted to make a distinction, would usually be classed as mechanical rather than civil engineering, and it would be at least a question whether it was not more than

the remainder of the work. In the case of bridge work generally, we should find the same condition of things existing in different degrees, according to the circumstances of each case.

Next, if we take up the subject of foundations and of drainage, which usually would be considered as pertaining strictly to the province of civil engineering, we shall find at once that the man who has charge of the engineering work of almost any large manufactory is frequently liable to have to put in a foundation, and every now and then it is a difficult one, to be built to support very heavy loads, and he may even be called on to build foundations under water, as, for instance, when the structure is on the water's edge, or on the shore, and where suitable works must be built to allow vessels to approach it to discharge or to take on their cargoes.

From what has been said it seems to me clear that no line can be drawn which marks off the work of the civil from that of the mechanical engineer, and that the kinds of problems which both are liable to have to solve are largely the same.

We are now prepared to consider what is the education which a young man needs to fit him for the profession of engineering whatever be the special line of engineering which he proposes to follow. And, before discussing on the details of what he ought to study, let us consider what it is that we desire to accomplish by giving him an engineering education. Naturally, we wish, as far as any education can accomplish it, to put him in the best condition to meet and grapple with the duties, the problems, and the responsibilities of his profession, as they arise.

There are two things which are absolutely necessary to make a successful engineer; first, a knowledge of scientific principles and of the experience of the past; and second, his own experience. The last cannot be given in a school, and each one must gain it for himself in his practice.

But the greater his familiarity with scientific principles and the experience of the past, the more able will he be to advance in his profession, and to be trusted to assume re-

sponsibility; indeed, if a man is ignorant of certain details and knows he is ignorant, he can—and if he is the right kind of a man, he will—take pains to learn them, if they bear on the work he has in hand; but if he is ignorant of scientific principles it is very likely that he does not know he is ignorant, or, if by good luck he becomes aware of the fact, it is next to impossible for him to devote the time and study necessary to correct his ignorance while his mind is busy with his daily work.

Moreover, a man who is not familiar with the scientific principles which concern his work is not a safe man to trust with responsibility; for scientific principles are merely the laws of nature, as far as known, as shown by the experience of the past.

Hence it is that the first and most important thing to be done for the student is to give him a thorough drill in the scientific principles, which find their application in his profession. It is in the school that this knowledge may best be acquired since it is only with great difficulty that principles can be mastered after the student begins practice, and then as a rule but very imperfectly; and this view is borne out by those engineers who have been successful, and who have had to acquire their knowledge of scientific principles little by little, and, as best they could, during the practice of their profession. Too much cannot be said by way of insisting that a thorough mastery of such scientific principles far outweighs in importance anything else that can be done for the student; and this is so true, that it is a decided mistake to neglect it in order to impart to him greater skill in such processes as will probably engage his attention the first year after he goes to work, as, for instance, to make him a skilful surveyor, a finished machinist, or an elegant draughtsman. Greater skill can far more easily be acquired after he goes to work, than can scientific principles, and if this mistake is made the consequences will probably pursue him throughout his professional life.

The two fundamental sciences upon which the scientific principles of engineering are especially dependent are mathematics and physics, and no proper course in engineer-

ing can be arranged without insisting upon these as fundamentals.

Let us begin with the subject of pure mathematics, and consider what portions should be studied, how they should be studied, or rather how they should be known, and of what service they are to the engineer after they have been mastered; bearing in mind that, in accordance with the opinions already expressed the course of study should be laid out with direct reference to the needs of the engineer; and that when it is so laid out, it will, by the very fact that it leads to a definite end, subserve best the purpose of true education, and hence of developing the powers of the mind. Probably the best definition of mathematics is that given by Prof. Benjamin Pierce, who defined it as "the science of drawing necessary conclusions." This definition, of course, includes formal logic, and hence embraces more than is ordinarily understood by mathematics. We may assert, however, that the only function of mathematics is to draw necessary conclusions from the assumed data. Mathematics has nothing whatever to do with the correctness or incorrectness of the data. If these are correct, the conclusions deduced by mathematics will also be correct, whereas, if the data are false, the conclusions deduced by mathematics will be false.

Thus, if we require the sum of a certain set of numbers, the process of addition will give the correct result, provided the numbers added are the right ones; but if the numbers added are not the right ones, the result of the addition will not be the one desired. Indeed, we might compare pure mathematics to a mill, it will only produce good meal when the corn furnished to it to grind is of good quality; and if the corn is poor the meal produced will be poor. With the selection of the corn which it is to grind, the mill has nothing to do.

No natural law can be discovered or proved by mathematics alone; the discovery or proof of natural law requires experiment and observation in all cases.

Just as arithmetic is a means of making calculations of certain kinds, so there are other kinds of calculations that

can only be performed by the use of mathematics higher than arithmetic; some kinds require algebra, some geometry, some trigonometry, some descriptive geometry, some analytic geometry, and some the differential and integral calculus; while others yet require higher mathematics. Now, inasmuch as every one can easily understand the necessity of arithmetic for the purpose of making the calculations, and drawing the conclusions which come within its province; so, it follows that the engineer should have a thorough working knowledge of whatever portions of pure mathematics he needs, to make the calculations that are liable to arise in his work, and also to draw the necessary conclusions which concern the engineering and scientific subjects with which he must deal in his profession. This latter is an all-important matter; for, if our prospective engineer is to be fit to assume responsibility at some portion of his career, before he allows himself to use a formula in practice, he ought to know just how it is deduced, and what are the assumptions that were made in deducing it.

The rule-of-thumb engineer ignores this matter, and allows himself to risk the money, the safety, and the lives of his fellow-men by making use of constants and mathematical formulæ found in some hand-book or elsewhere; using these constants and formulæ blindly, without knowing how they were deduced, or whether they have any reasonable foundation to stand on; or, in other cases, contents himself with merely guessing at what should be the dimensions of the various parts of a structure or machine. The natural result of such a course is poor work, and often disaster: and the world is rapidly waking up to this fact, so that important engineering work is being less and less entrusted to these rule-of-thumb engineers.

Now, I may say that knowledge of at least all these subjects mentioned in my communication—through the differential and integral calculus—is necessary for our prospective engineer.

As to descriptive geometry, that is classed by many, not as mathematics, but as a branch of drawing. It is the mathematical work upon which the making of engineering draw-

ings of all sorts is based, and hence I have put it in this list.

So general has the conviction become that the engineer needs some knowledge of the differential and integral calculus, that it is not necessary for me to cite cases where he must use it if he is to perform his work intelligently and not by rule-of-thumb. Differential equations is a subject which is sometimes classed with the differential and integral calculus, and sometimes as a separate subject. It is one that should, if possible, be learned at least to a small extent, though the more that is known about it the better.

As to the special work to be done in each of these subjects, it is a matter of judgment with the one who lays out the course, and I shall not weary you with these details; but I must explain what ought to be the result aimed at, in other words, how the student should know his mathematics.

I might express my idea by saying that he should acquire the ability to use it as a tool, but, when I say that, I mean not merely as a tool for making computations, but also as a tool for drawing necessary conclusions of the kinds that apply to his engineering work; and this last is the feature which is most frequently lacking in the mathematical instruction given to engineering students.

By one method often pursued in teaching mathematics, the student is made to grind through a certain round of operations over and over until he has been so drilled in performing them mechanically that he can *perform* a similar problem. By this method, he is only taught to use it as a tool for making computations.

Another method, often pursued, is to exercise the student's ingenuity in performing a variety of (sometimes puzzling) problems which are of purely abstract interest, and are not planned in such a way as to bear upon the class of problems liable to arise in engineering work or study. This course probably tends to make the student do more thinking, but does not direct his thinking in the channel most useful for the prospective engineer. To accomplish the desired object in the teaching of mathematics, it is, of

course, necessary that the teacher should be able to grasp the requirements of the engineering courses, and should know the special kind of use that the prospective engineer will have for his mathematics later in life.

Another important matter, the accomplishment of which concerns the treatment of the subjects of a mathematical nature that follow in his course, rather than the treatment of the pure mathematics itself (though the mathematical department can help in this matter), is that the student should be taught to distinguish between the mathematics of the work, and the assumptions made at the beginning, or in the course of it, respecting the proposition he is dealing with. The student is prone to fail to draw this distinction, and to consider things that are pure assumptions—sometimes based on facts and sometimes not, sometimes true under one set of conditions and not under others—as being the deductions of pure mathematics, and hence, as conclusively proved and applicable under all conditions. Such a course is fraught with danger for the student who does not understand and grasp what are the conditions of the problem he is dealing with, and who is therefore liable to apply the result to cases when the conditions are entirely different, and where, consequently, the result is not at all applicable. He is also prone to consider as demonstrated, things which are not, but which are only proved to hold, provided certain assumptions are true; whether these assumptions are true or not being left for experiment to determine. In cases where certain approximations are made which are justifiable under certain (perhaps the ordinary) conditions, the student who does not observe what these conditions are, is tempted to use the approximations when they do not hold, and hence to deduce wrong results.

For example, I have seen a long mathematical (so-called) demonstration claiming to prove something which was manifestly absurd, wherein the mathematical work was all right, except that a certain quantity was neglected which, under ordinary circumstances, was small, but which in this particular case was infinity. To the student who had not the grasp on his mathematics which would enable him

to see what had been done, it would have appeared that the absurdity had been proved.

Perhaps I might sum up a part of the above by saying that the student should be taught to think, and that the attempt to teach him to think should begin as early as possible in his course, and be kept up throughout. It is much easier for the average student to learn a lesson to recite by rote even if it contains a lot of formulæ, than it is to do a little solid thinking himself, and yet the more we can make him think the more successful in every way will he be.

It may be well to mention in connection herewith another matter of great importance, and which is too often not properly considered by some of those who teach the subsequent engineering studies.

The teachers I have in mind have had a training in pure mathematics which was not laid out with any reference to a subsequent engineering course, but such as had become customary in the colleges, with a view to general training only. In such a course, certain equations, certain courses of abstract reasoning, certain steps have become, as it were, crystallized; and these teachers adapt their engineering work to these crystallized forms. Thus, if a certain problem is to be attacked which could be regarded mathematically as a special case of some more general problem, they would always approach it through the general case, whereas, though this general case might logically precede it if we confined our thoughts to the calculation, its generalities might be of such a nature as to have nothing to do with any case that the engineer would ever have to deal with.

Now a teacher who takes this view, requires his students to perform a large mass of purely mathematical work, for no purpose, and, worse than that, he draws away the attention of the student from a proper consideration of the assumptions, of the data and of the scientific principles involved in his problem, whereas these should be the matters uppermost in his mind, while his mathematics should be a tool with which he is thoroughly familiar, and which he can use freely and correctly to draw neces-

sary conclusions in the problems with which he has to deal. In the early days of engineering schools when the science of engineering was not as fully developed as it is to day, this would naturally be, and was the course taken by the more educated teachers of, and writers on, engineering subjects; and, on the other hand, the large amount of irrelevant mathematics, the paucity of experimentally ascertained facts applicable to engineering work, and the liability of the young man to fail to examine critically the truth or falsity of the assumptions, which were almost hidden under such a mass of mathematical equations, and hence his liability to consider as demonstrated truths things that were subsequently proved by experiment to be untrue; have doubtless been responsible for a large number of the objections that have so often been made to a mathematical training for the engineer; and in many cases where a man speaks against the use of mathematics in engineering, we shall find, if we examine carefully, the spirit rather than the letter of his objections, that what he really objects to is just the erroneous use of mathematics where a man always works out the solutions of his problems with a lot of equations, but does not take pains to examine first the assumptions at the basis of his work. But now that engineering science, and also engineering schools are much more fully developed, this kind of teaching is fast dying out, and with it the purely empirical work and teaching which is the opposite extreme and which is fully as baneful in its results.

Perhaps those of you (if there be any) who teach mathematics may think that the standard I have set is high. I admit that it is, and also that it requires hard work, good judgment, and the qualities of a good and efficient teacher, not only in laying out the course, but even more in teaching the class. Nevertheless, this standard is the one that is needed, and good judgment, and good teaching can at least approach near to it within the time that can be afforded in our engineering courses, even with such previous mathematical preparations as can be obtained to-day by the students before they enter the engineering schools; and as fast

as it becomes possible to raise the standards of admission, the standard I have set can be even more fully realized.

The other fundamental science which I have mentioned is physics. It may be defined as that department of natural science which treats of the laws governing the various manifestations of energy (as gravitation, sound, heat, light, electricity, etc).

It deals with natural law as it applies to just those classes of bodies, and substances with which the engineer does his work. Indeed, physics is a very general term, and might be made to include a great many subjects that are usually called by some more special name. For instance, mechanics is sometimes spoken of as a separate science, and sometimes as forming a part of physics, and, moreover, under any definition physics includes a part of mechanics.

Practically, a course in physics is the suitable preparation for a proper understanding of the scientific principles of most of the engineering work with which the student will come in contact. Treating, as it does of the laws of nature, the more thoroughly an engineer knows it, the more successful will he be, and an ignorance of these laws can only result in failure,

Mechanics, light, sound, heat, and electricity, are all matters that concern the profession of the engineer so intimately that he cannot afford to neglect a careful study of their first principles. It is unnecessary for me to say, therefore, that there is no portion of the work usually treated in the best and most thorough courses of general physics but what should be included in the course of our prospective engineer.

Then, a certain amount of work in the physical laboratory is of great importance for the student, for it teaches him how to ask questions of nature, and how to get correct answers; in other words, how to make careful and accurate experiments, and this is a matter that intimately concerns the engineer. It is true that the greater part of his experimental work will have to be performed on a considerably larger scale than that usually carried on in a physical laboratory; but, on the other hand, some of his most im-

portant and delicate work involves the doing of just such experimental work as he is taught to carry on in a well organized and well equipped physical laboratory; and also the performance of these physical laboratory experiments is a proper introduction to his later course of experiments on the large scale, drilling him in accuracy and care while working on small amounts of material.

Indeed, I might mention quite a number of experiments which are all-important to the engineer, and in regard to which, it would be difficult to decide whether they should be called physical laboratory or engineering laboratory experiments, since they often have to be performed in both. Thus, the calibration of thermometers is a matter that is properly taught in the former, and yet the engineer who is to do delicate engineering work is liable to have to calibrate his thermometers, or at least to make a careful and accurate comparison with a standard which he or some one else has calibrated. Again, the determination of the mechanical equivalent of heat is a matter of vital importance to the engineer, but the best, and most accurate work thus far upon the subject has been done by Professor Rowland, a physicist, in his physical laboratory.

As a rule, when experiments are to be performed on the large scale they get beyond the possibilities of a physical laboratory. In this category we may place such experimental work as the testing of steam engines and steam boilers, the testing of the strength of materials of construction on a practical scale, etc., but, in order to carry out these tests with proper accuracy we have generally to perform delicate measurements, as, for instance, measurements of temperatures, etc., in the first, and measurements of very small elongations or shortenings in the second case, and consequently have to use the suitable apparatus with the necessary degree of accuracy.

Since we have just been considering mathematics and physics, which may be called general sciences, perhaps a few words should be said in regard to chemistry. I cannot claim for it a similar position of fundamental importance in the engineering part of an engineering course

that belongs to mathematics and physics. Nevertheless, a certain amount of chemical knowledge is of great importance to all engineers, but when they have passed this point, although a farther knowledge would be useful, it is not one of the most important things. The chemical composition of fuels, of steels and irons, of cements, of oils, and of other materials is a matter that directly concerns the engineer. It is true that he can usually have his chemical analyses made for him, and generally would better do so; but he must know enough of chemistry to understand the bearing which the chemical composition of his materials have on their use in engineering work. Some knowledge of industrial chemistry is also desirable, so that he shall understand the nature of the processes performed in manufacturing in which chemical processes on a large scale are performed.

The instruction in chemistry should, if possible, be given very early in the student's course. In the case of the Massachusetts Institute of Technology, and also, I think, in that of several other schools, both lectures and laboratory work in chemistry are given in the first year, and when this is done the instruction in chemistry fulfils another important function, viz: it introduces the student at the very threshold of his course to a species of scientific work that obliges him to think, and this, in a direction in which, as a rule, he has not been trained in the preparatory schools. Especially is this true of the laboratory work, for, by observing the results of experiments which he himself makes, he must learn how to interpret the replies of nature; and as chemistry, unlike mathematics, is an experimental science, it trains the thinking powers of the student even more than do his algebra, geometry and trigonometry.

We will next consider the subject of drawing. That this is an absolute necessity to the engineer I think no one will deny.

Drawing, to a great extent, is his language. It is the method by which he expresses a large class of his ideas. Go into any extensive shop or manufactory where they make a business of manufacturing machinery or of building

structures, and you will find that all operations are controlled through the draughting room. Drawings must be made of every piece that is to be manufactured, and of every machine or structure that is to be erected, and either the drawings themselves, or tracings made from them, or blue prints taken from the tracings, are sent into the shop, and these form the instructions of the workman how to make the pieces. In many establishments, it is the chief draughtsman who has charge of designing the machines and structures, so that when this is the case the chief draughtsman becomes practically the engineer of the establishment.

Moreover, neatness and accuracy must prevail in the drawings, so that they can be easily understood, for a mistake made by the draughtsman on a drawing, or a misunderstanding of the drawing by the workman, if not discovered in time, may result in a large pecuniary loss to the manufacturer.

Freehand drawing and lettering are both very important matters, *i. e.*, freehand drawing is needed to such an extent as will enable the young man to sketch easily and readily any part of a machine or structure, and to do this work with sufficient speed and clearness to be able to complete it while he has access to the machine, so that he can subsequently make a complete set of working drawings from his sketches, a thing which is often necessary when a draughtsman is sent outside for information. Neat lettering and dimensioning add very materially to the clearness of a drawing, and hence render it less likely to be misunderstood; and this is especially necessary since the workman should always be instructed to make use of the figured dimensions, and should never be allowed to scale a drawing.

Graphical methods are sometimes employed for the making of calculations necessary in the designs of machines or structures, and when these are used, of course, great accuracy is an absolute necessity in making the drawing. Seeing now that drawing plays so large a part in any engineering work, let us consider how it should be taught, and how the course should be laid out.

We may say that there are two objects to be accomplished, the first being the execution, and the second the power to express ideas by means of drawing, and to read the ideas of others, which have been expressed by the same means; in other words, to be able to produce, from the piece itself, the necessary working drawings, and *vice versa*, when, having the working drawings, to be able to understand how the machine is made in all its details.

A certain amount of time will have to be employed at the outset to teach the use of instruments and to enable the student to perform the actual work of drawing, observing, of course, accuracy and neatness. But as soon as this necessary preliminary training in execution is accomplished, so that the pupil begins to do his work with a fair degree of accuracy and neatness, then the attempt should be made at once to have him acquire the language, so that he can readily translate ideas into drawing, and *vice versa*. Now, the mathematical basis of drawing is descriptive geometry, hence the student should be set at once to study descriptive geometry, being made to work out and demonstrate the propositions on the blackboard, as in any other mathematical class-room exercise; and he should be made to take a broad view of the subject so that he will understand the drawing, whatever be the angle, whether first, second, third or fourth, in which it is made, or if it is partly in one and partly in another. I do not believe in the method that confines him to the first angle for a long time, until he gets so used to that particular angle that the moment a figure is placed in any other it looks difficult to him. Indeed, in practice all angles are used, but if one is employed more than others it is the third and not the first. But the student has only obtained a firm grasp on the subject when he is equally at home and familiar with the figure in whatever angle it is placed.

Then, parallel with the class-room work, where he is taught the theory, or, in other words, descriptive geometry, he should be obliged to make correct and accurate drawings, giving the constructions for a certain number of the problems of descriptive geometry. The only difficulty in

the matter will be found at the very beginning in making the student exercise his imagination sufficiently to grasp the central idea of projections in any of the angles. In this he must be thoroughly drilled; the rest is then easy. I might add that here also the teacher should have in view in laying out the propositions to be studied by the class, the needs of an engineering course; and while they should be comprehensive, and cover all the main principles, they should be chosen from the point of view of engineering and not from a desire to keep as nearly as may be to the course which was originally given by Monge, the father of descriptive geometry.

Now, when our student is familiar with descriptive geometry, and has made reasonable progress in execution, and understands how to express ideas on paper, at least as far as descriptive geometry goes, the next step to take is to cause him to make working drawings from measurements made by himself of pieces of machinery, or of structures; thus teaching him how to determine what views of a piece it is necessary to make, how to arrange the drawings on paper and how to dimension them.

However, at the outset, we are confronted with the fact that every different works has its own system of making drawings, differing from one another in some minor details, usually in the manner of putting on dimensions and sometimes in the manner of putting on shade lines, or some other minor things; *i. e.*, things about which it is of minor importance which system is followed, but where it is of the very greatest importance that some one consistent system should be employed.

Now, some one good system ought to be chosen, and the student should be made to adhere to it. Also such conventions and rules as are universally adopted should be taught him, such for example, as that the diameter and not the radius of a piece that is to be made in a shop should always be designated; that the over-all dimensions of pieces should always be given, etc.

After the student has done a reasonable amount of this kind of drawing, which might be called drawing from

models, he should next be required to make the detail drawings for the separate pieces of some machine, and having done this, should make the assembly drawings from these detail drawings, thus learning how the separate pieces are to be put together to form the complete machine, to detect errors in the detail drawings, and how all this is to be represented on paper. Such a course of instruction is necessary in order to give the student the training needed to enable him to carry out the reverse process, which is the course he will most frequently have to follow in the draughting-room of the works.

For drawing, pure and simple, such a course as that outlined will probably give a reasonable skill in executing and in making and reading drawings. Of course, however, there ought to be, if possible for all, and without fail for those who are aiming towards topographical work, a reasonable amount of drill in topographical drawing; then for all there should be, as I have said, instruction in freehand drawing, and also in plain lettering.

As to the drawing done in connection with the other work of the students, which would naturally form a very considerable portion of their total drawing, I shall not speak here, for it belongs in connection with the other work; the students are supposed to have acquired the language of drawing and to use it whenever needed.

Perhaps I ought to mention, also, that all engineering students should be taught to make blue prints, an easy matter as far as teaching it to the student goes, but one of the greatest importance in practice.

It is almost impossible to understand to-day how we ever could get along in our large shops and manufactories of machinery and of structures without the use of blue prints. In former times drawings had to be made, of course, of all the parts of the machine, and then tracings of each part to send to the shop for the use of the workmen. These tracings were often spoiled in the shop, and more had to be made, involving a large amount of labor; also, if the purchaser of the machine wished a tracing, one had to be made for him. As things are now, the original drawings are generally

made in pencil, these being seldom inked. Then one tracing is made, and from this are taken as many blue prints as are desired. If one is lost or spoiled, it can be replaced with very slight labor and at small expense.

Next comes mechanism, which may be said to be the most elementary of the subjects that are commonly considered to constitute the strictly professional work of a mechanical engineer. It deals with the combination of the motions by means of which each machine is enabled to accomplish its own special functions when the power has been furnished to it.

Were I to undertake to give a list of cases where the invention of certain special mechanisms have revolutionized certain industries, or have advanced enormously the industrial progress of the world, or caused a great saving of labor, and brought about incalculable benefits for mankind, my task would be almost endless.

The invention of different combinations, and, hence, the introduction of machinery of different kinds, by means of which the industrial progress of the world has been rendered possible, began in the very earliest ages, long before the advent of steam, and even back in the days when the only sources of power were the work of men and of animals. Indeed, had it not been for machinery the industrial progress, and, hence, the civilization of the world would have been impossibilities. There would have been no commerce, and no occasion for roads or means of communication, for the world would have remained in a savage state. Consider what was the condition of the textile industries even just before the time when Hargreaves invented the spinning jenny, and Arkwright the spinning frame, and Crompton the mule, compared with their condition to-day, and you have an example, in one department, of what machinery has rendered possible, and of how incalculable are the benefits that it has conferred on mankind. Then they had only the hand-spinning wheel, and the amount of work that could be accomplished was very small. The inventions of Hargreaves, of Arkwright and of Crompton were merely combinations of mechanism, and, although they still used

manual labor or horse-power, the amount of yarn that one person could produce was many times what could be accomplished by the same person with the hand-wheel. To-day we should look upon these machines of Hargreaves, Arkwright and Crompton as exceedingly crude, and instead there has been developed all the wonderful variety of marvellous machinery that hums in the different textile manufactories of the world, furnishing us with all the delicate and rich fabrics with which we adorn our persons and our houses at the present day, our cotton goods, our woollens and worsteds, our silks and satins and laces, our carpets and our tapestries, etc.

Coming down to a later date, consider the enormous saving of labor, and the enormous increase in the product of the labor of one individual, by the introduction of the sewing machine, even leaving out of account the fact of driving it by water or steam power. Consider how very general is its use, that one can hardly enter a private house that is without one, to say nothing of the enormous number used in manufactories of clothing and of other articles which are made by sewing.

Furthermore, it has found its way, with some modifications into the manufacture of shoes; and in this industry we find a great number of special machines in use which are simply combinations of mechanism designed to accomplish certain special results.

Then consider the tools used in our machine shops, and places where machinery is manufactured; the lathes, the planers, the drills, the shapers, the milling and the grinding machines, the gear cutters, and the host of special machines in constant use all over the world.

Consider the bolt and nut machines, the machines for making barbed wire, the nail machines, the screw machines, and a host of others too numerous to mention. To call them labor-saving devices is a misnomer, for they rather render possible the work of the world, such as it is at the present day, which would be an utter impossibility without their aid.

The methods of combining the different parts of a

machine, so as to obtain the desired motions, have been reduced to a system, and this system constitutes the study of mechanism.

It aims to make the student familiar with the methods by which such results are to be accomplished, and to teach him the principles governing them, so that he may undertake intelligently the devising of new arrangements, and may avoid making or proposing absurd, impossible or unadvisable combinations. It depends mainly on pure mathematics and involves a knowledge of drawing. The mathematics principally needed are algebra, geometry, trigonometry and descriptive geometry, while it is very useful and will often save work and enable one to reach results more easily to have a knowledge of analytical geometry and calculus.

Drawing is, of course, indispensable also. We might well say that mechanism is a mathematical subject, and teaching it requires the use of the class-room and the drawing-room. To a certain extent it is desirable and almost necessary to use models also, but care should be taken that the student fully understands a drawing; for if, in order to work out a combination, he finds it necessary to build or look at a model before he can predict with certainty what it will accomplish, he has not properly learned his mechanism. In order to have a knowledge of the subject that is sufficient to enable him to make real use of it in practice, he must be able to put his ideas into shape in a drawing readily and quickly, and to predict the mode of action from this drawing and such mathematical calculations as he may make. If, on the other hand, a drawing is presented to him, he should understand how the machinery represented will behave, and what can be expected of it. Moreover, he should be able to do this with mechanism of very considerable complexity, for he will often meet with such machinery in the course of his practice.

Now, after he has had his systematic study of mechanism, it seems to me that it is of great importance that he should make a study of the usual machine tools that are in general use to-day, such as lathes, planers, milling machines, etc.,

studying first the characteristics of the usual mechanisms they contain, noticing the reasons for choosing some and not others; as, for instance, the questions of stiffness, of wear of the surfaces, of stability, etc. Of course, he should have an opportunity for studying some forms of these by personally inspecting them in the shops attached to the institution, but these are necessarily limited in size, and there is also an enormous variety of other combinations in common use for different purposes. This work can best be accomplished by the teacher, probably, if he puts in the hands of the students a large and systematically selected collection of cuts of the machines in general use made by some of the best makers. The teacher, of course, must be familiar with these machines, and he must be able to explain to the class their general as well as special features, and see that the student becomes familiar with them. A little instruction of this sort will be of great service to the student in many ways, both in his course and in his subsequent work in the practice of his profession.

Another thing that, in my opinion, is very desirable to do by way of making the student's study of mechanism serviceable to him, I will now explain.

In the study of machine tools just referred to, the student gains a familiarity with the characteristics of those kinds of machinery which he will meet with at every turn; but, as a rule, the ordinary machine tools cannot be said to involve a very large amount of complicated mechanism; hence, something should be done by way of making him thoroughly familiar with certain classes of machines that, in order to accomplish their objects require a large amount of very complicated mechanism. Hence, he should be taught the construction of some such machines in all their details, and then, if possible, he should find in the laboratory examples of some of these machines, and be made to understand them in detail—as it were, to dissect them, to see for himself that they do accomplish what is claimed for them, and to verify, by his own computations from the dimensions of the parts, whether the actual motions are such as agree with his calculations; and if not, to find out why they are not,

or, in other words, wherein he made his mistakes in calculation. Now, it matters comparatively little what kinds of machines these are, provided only that some of them, at least, involve a very considerable complication. In the case of our own classes, we have a lot of textile machinery, the most complicated of which is a spinning mule; and the students are required to become thoroughly familiar with the action of all the parts of these machines. For example, in the case of the mule, they must understand thoroughly what is the mechanism for carrying out and returning the carriage, and how this is caused to vary its speed at different times; what is the mechanism that does the twisting; what the winding; how the roving is drawn out in the beginning, etc. By having such a machine in the laboratory the student can be made to study and understand it; whereas, in a mill the mules could not be stopped and run at his convenience and for his benefit. Moreover, after the student has had a good course in mechanism, and has then had to render himself familiar with all the parts of a machine as complicated as a mule, he is better prepared to grasp and understand complicated mechanism of any kind; as, for instance, a barbed wire machine, a bolt and nut machine, an automatic screw machine, etc.

Then, again, there is a special class of problems in mechanism, which concern machines that generate power, as the mechanism of the steam engine; but the one portion of the mechanism of the steam engine that requires special attention is the valve gear. Hence, the student should have such thorough instruction in valve gears and link motions as shall drill him in the mathematical principles for working out valve gears in all their details, and should also be taught the different ways of designing and making those in use to-day, the ways of constructing them and their adjustments, all this being really a part of the mechanism course.

Now, although I have already met and answered a question that might arise in the minds of some, it will, perhaps, be worth while at this point to raise and answer it again. It is this: Is it as important for the young man who ex-

pects to devote himself to what is commonly called civil engineering to be thoroughly drilled in mechanism as it is for the mechanical engineer? and I answer very decidedly, yes. The civil engineer who is to build bridges or engage in some of the kinds of engineering which I enumerated under my list of so-called public works, cannot carry on any work of any magnitude without having to use a good deal of machinery, and is liable to have to use special machinery; and the more important the work on which he is engaged the greater the use he has for machinery of all kinds; and if the development that has taken place up to the present time is any sign of what is to take place in the future, he will be more and more intimately concerned with the use of machinery, which he will need to direct, to set up, and perhaps even to design.

Another matter to which it may be well to refer is that a thorough knowledge of the principles of mechanism will tend to guard the prospective engineer against the danger of inventing absurd and impossible combinations of mechanism and impracticable machines, or to expect to accomplish by means of mechanism only results that cannot be accomplished by it alone.

Indeed, were I to attempt to give you a list of all the worthless and absurd inventions of the world, I should probably find that the greatest part of them consisted of some form of mechanism. The very fact that the invention of certain machines, *i. e.*, of the mechanism of those machines, has had such a powerful influence on the welfare of mankind is, of itself, an invitation to a great many people who are ignorant of scientific principles, and also of the requirements of machinery, to try their hands at inventing, and the patent offices of the world contain an enormous number of such worthless contrivances.

The next course of which I shall speak is one which vitally concerns the engineer at every turn, and, therefore, one in which it is absolutely necessary that he should be very thoroughly drilled. The course to which I refer is theoretical and applied mechanics. This term has been used in different senses at different times, and in different

places, but the sense in which I shall use it is that which is now most generally accepted; *i. e.*, it includes a general and mathematical discussion of the action of forces upon bodies at rest or in motion, and also a full treatment of the strength and elasticity of the materials used in construction, both from a mathematical and also from an experimental point of view. To speak more in detail, it includes a treatment of such subjects as the following, *viz.*: composition and resolution of forces, conditions of equilibrium, determination of the centers of gravity, of lines, areas and of solid bodies; the general laws of dynamics, as a treatment of uniform and varying motion; the pendulum, determination of moments of inertia, and of centers of percussion, etc.; the laws of friction; determination of the work used up in friction, both by mathematical calculation and by actual experiment. Then come the determinations of the stresses in the different members of trusses of all sorts; and then a study of the mathematical discussion of the theories of the strength and elasticity of materials, *i. e.*, study of the distribution of the stresses acting in tension rods, struts or compression pieces, beams or other pieces bearing a transverse load; also in all sorts of pieces that are subjected to shearing, including, of course, riveted joints, shafting and beams, as well as in other pieces; the distribution of the stresses acting in a hook, or in any tension or compression piece that has to bear an eccentric load; the determination of the greatest intensity of the stress, or, in other words, of the stress acting on the most strained fibre in each case; also the determination of the strains (elongations in the case of tension, and shortenings in the case of compression pieces) that occur in all the different parts of the piece; the modes of determining the deflections of beams, the angle of twist of shafts, or the amount of yielding of pieces generally, under load; theories and modes of calculation of the stresses at different parts of continuous girders, *i. e.*, beams which are continuous over more than two points of support; also of the deflections of, and the shearing stresses of, such beams; determinations of the stability of, and of the stresses acting in, arches which bear a load, whether they

are of stone or iron; theory of the stability of domes, and then a study of the theory of elasticity.

Turning to the experimental side, the student should be familiarized with what experiments have been made upon and what results they have shown as regards the strength and the stiffness of such pieces as are used in construction to bear a load. Moreover, the account of these experiments should be brought up to date, and special emphasis laid on the results of those where the conditions of practice, as to size, manner of loading and treatment generally, have been exactly, or at least approximately, copied. The student should be made to study carefully the results that have been obtained in these experiments, to collate and compare, and to draw from them such conclusions as are warranted, to see how far and in what ways they may modify the ordinary mathematical calculations and the ordinary ideas in regard to the action of such pieces in bearing loads. To study the effects of the repetition of stresses to which pieces are very frequently subjected in practice; in short, to put himself as nearly as possible in such a condition that he knows what is the extent of our knowledge of the facts as shown by experiment in regard to the behavior of the materials of construction, wood, iron, steel, stone, cement, concrete, etc., when subjected to such loads as they have to bear in practice.

It would seem almost unnecessary to say that such subjects as the above are of the most vital importance to the engineer, and yet, absurd as it may seem, there have been those, and there are still occasionally some, who consider such information as of no consequence. These are the men who believe in doing their work by rule of thumb; and they would proportion the parts of any machinery or structure which they might have to build by one of two methods, either of which they would call practical, for the reason only that it lacks the element of scientific knowledge. The first method is, if the thing to be designed is similar to something that they are familiar with, to copy that—whether it is right or wrong, whether it is far stronger than need be, or on the verge of collapse—simply because

they are following a precedent; if it is to be of the same sort as something that has gone before, but is to be of greater or less capacity, they are very liable to determine the sizes of the new one from those of the old one by the rule of three; or, if the new machine or structure is wholly unlike anything they have seen before, or if, though like something they have seen before, they decide not to copy the old, they determine what dimensions to give it by guessing, and call their guesses practical experience, notwithstanding the fact that they are often very poor guesses.

The second, and more usual method which such men are liable to follow, is to determine the dimensions of the pieces by means of formulæ found in some handbook, and they assume that because a formula is found in a handbook, or rather in the handbook which they have adopted as authority, therefore, it must be right, trusting blindly to the correctness of the formula and constants given in these handbooks, although they have no knowledge of the assumptions made in the deduction of the formulæ, nor of the experimental basis upon which the determination of the constants rests.

It is needless to say that either of these methods is liable to, and often does, result in disaster, and accident after accident has resulted from, and lives have been lost in consequence of, the use of each of such methods as these.

The consequences of structural weakness in any member of a structure or machine are:

- (1) Lack of the necessary stiffness, and hence, in the case of a machine, the turning out of poor work; or, in the case of a structure, oscillations which render it unsuitable for the performance of fine and accurate work of any kind.
- (2) Breakage of the structure or machine.
- (3) Injury to surrounding objects, personal injury, and perhaps loss of life.

Hence it is very important to provide the requisite strength and stiffness in all the members of the structure or machine. Increase of the amount of material does not necessarily mean increase of strength.

The first step towards determining the proper dimensions for any piece, in order to secure the requisite strength and stiffness, is to know the forces acting upon it, and how they act.

Then we need to determine the stresses to which the piece is subjected, in consequence of the action of these forces, and also the strains, *i. e.*, the elongations, compressions, deflections or deformations due to these stresses.

Next, whether the forces are quiescent, or whether they are oft-repeated, and what are the conditions of the repetitions.

Then we are ready to determine what dimensions we must adopt in order that the greatest stresses at any point shall not exceed an amount consistent with safety, this amount being determined by experiments made upon the strength of the material, and so that the greatest strain shall not exceed an amount consistent with safety and with the proper stiffness of the machine or structure.

If, for instance, we are to decide upon the proper dimensions to adopt for the different pieces that compose a machine, we need to ascertain, first, what is the greatest force exerted at that end of the train of mechanism where the work is done. It becomes then merely a question of composition and resolution of forces to determine the forces acting on any one piece of the machine. We shall thus find, in general, that some pieces are subjected to direct tension, some to direct compression, some to a transverse load, some to torsion, some to a combination of different stresses, and some to various eccentric loads.

Suppose, now, that we have a structure, for instance a building. We must first ascertain the greatest loads that can come upon any part of the floors, and then determine the stresses produced in the beams, columns, walls, etc., by these loads. But we must also observe that the greatest stresses are not necessarily those produced by the greatest loads, and hence we must determine the loads which produce the greatest stress in each member. Similar remarks apply to a bridge structure.

A few examples will serve as illustrations. Take the

case of one of the columns of a building. When the greatest load per square foot covers the entire floor above, the resultant of this load on that floor acts along the center line of the column, and the stress per square inch due to this load is uniformly distributed over the section. When, on the other hand, the floor on one side is fully loaded, and the floor on the other side is not loaded, then the total load is less than in the other case, but its resultant does not act along the center line of the column, but is eccentric. Now, it is plain that the eccentricity of the load introduces a tendency to bend, and, under such conditions the load that will break the column is very much less than it would be when the load resultant is central.

Now, when a column in a building is to be calculated, we should determine what is the greatest stress on one side, due to having as great an eccentricity of load as is possible to be attained in the use of the building, and we should see to it that the dimensions of the column are such that this greatest stress shall not exceed safe limits. Further, if with most of the sizes of columns used in buildings we were to determine the amount of this eccentricity, and also the probable amount of the deflection under any central load that the column would have to carry while in use in the building, we should find that the latter is almost inappreciable compared with the former, and yet it is not at all common for people to-day to compute the stresses due to the eccentric loading, and instead they often use some formula which was devised for central loading, and which was deduced by making certain assumptions in regard to the deflections which experiments on actual full-sized columns do not bear out.

This I call neglecting the important consideration and performing a great deal of computation on a very minor one, by means of a formula that cannot be proved, but which is given in the handbooks. Is it any wonder that columns sometimes fail?

Another illustration is to be found in connection with the calculation of fly-wheels of steam engines. Every once in a while we hear of the bursting of a fly-wheel, the frag-

ments of which have, in consequence of the breakage, been hurled like so many projectiles, in all directions, carrying death and destruction in their paths.

Now, in several cases of wheels which I have examined, the stresses existing in the bolts which unite the separate sections of the rim, and the stresses in the portions of the rim near the joints, were decidedly greater than a due regard for safety would allow, and greater than the designers of the wheels would have allowed had they been designing some other construction, or had they realized their existence in the case of the wheel. The difficulty in these cases, apparently, was that the designer, if he figured at all, disregarded the fact that the bolts were not placed in the line of direction of the resultant of the tension in the rim, but were located on one side of that line, and that therefore they had an eccentric load, and, having neglected to figure the extra stress due to the eccentricity of the load, he did not provide sufficient strength in the wheel to resist it.

Another way in which erroneous results may have been reached is in the misapplication of a rule given in Rankine's books, which applies only when the load is not eccentric.

Another case where disaster occurred in consequence of neglect to consider the effect of an eccentric load (well known to a Boston audience), is afforded by the Bussey Bridge accident, which occurred a few years ago, where, as will be remembered, one of the hangers had a very eccentric pull, while it was only strong enough to bear the load if it had been central. This disaster was the cause, not only of a serious destruction of property, but also of a large loss of life.

Let us turn next from a consideration of the formulæ to the question of the proper constants to use.

If the dimensions proposed for any piece are such that the greatest stresses and the greatest strains in the piece are no greater than the safe allowable stresses and the safe allowable strains, respectively, for that kind of material, then the dimensions chosen are such as are consistent with safety; but if they are larger, the dimensions must be

altered so as to bring these greatest stresses and strains within safe limits.

The knowledge of what are safe limits is, of course, an important matter, and can only be determined by experiment.

This principle has, of course, been generally acknowledged for a long time by those who believe, as they should, in calculating the stresses that actually exist, and a great many experiments have been made, and the results of such experiments have been published, and are quoted in books, and, of course, in the handbooks. Now, there are many who accept, as necessarily correct, the constants given in their favorite handbook, without stopping to ascertain under what conditions the experiments were made, and whether or not these conditions are similar to those which exist in the cases they themselves have in hand. The result of such a course is the frequent use of values for allowable stresses which are not suitable to use at all, or which, while suitable in some other case, are not suitable to use in his own case. To make this matter plain, let us use a few illustrations:

In the different handbooks are given various rules and constants from which to determine the breaking loads of wooden columns. Taking the condition of the handbooks a few years ago, the engineer would have found, if he chose to hunt up the records of the experiments upon which most of these constants were based, that their only basis was seven experiments selected out of seventeen, which were made about the year 1840, upon seventeen columns cut out of one good plank of Dantzic oak, which had been cut up and seasoned about one year, the largest piece tested being about two inches square and five feet long; and that since the results obtained from the seventeen did not run very uniformly, ten were thrown aside, and the other seven were used to furnish the constants for the formulæ; and further, that most of the formulæ given in the handbooks took their constants from these experiments, and applied them indiscriminately to wooden columns of all kinds of wood. Moreover, while a few other formulæ were given at that time, they all derived their constants from experiments on small speci-

mens, and made under conditions which rendered them unsuitable to use in actual practice; *i. e.*, the breaking strengths as figured by means of these formulæ and constants were very different from the actual breaking strengths.

Now that experiments on full-size columns of wood have been made, it is found that different kinds of wood differ very considerably in their crushing strengths: that oak, in regard to which the prejudice has almost always existed that it is stronger than yellow pine, is really not as strong as the yellow pine; and that all the figures that are suitable to use for the crushing strength of timber columns of practical size are very decidedly lower than those given by the results obtained by the Dantzic oak experiments already referred to.

When we stop to consider the reasons for these facts, they become evident, *viz.*: There exist in timber columns of the sizes and proportions used in practice, knots, season cracks, defects and a lack of homogeneity which do not exist in small selected pieces. Hence, since modern experiments made under the conditions of practice have shown us what are really the values suitable to use in computing the breaking strengths of timber columns, it follows that these old constants were entirely inapplicable.

As a matter of fact, a very considerable number of the handbooks and other books now give the new instead of the old constants; but other authors, either through obstinacy or inertia, have not changed their books to keep up with the times in this respect.

In the case of timber beams bearing a transverse load, the number of experiments made on small pieces, about two inches square and five feet long, is very large; and the constants almost universally given in the handbooks until a very recent date were based upon experiments of this kind. The results, however, differed a good deal among themselves, as they were obtained from different sets, but all are decidedly larger than those that have been obtained from modern experiments made on beams of such sizes as are used in practice, and for the same reasons that were explained in the case of timber columns.

The condition of things to-day, therefore, is that some of the handbooks still adhere to the old constants, differing, however, among themselves, and that others have brought their books up to the times in this regard, and give the new constants derived from the modern experiments, although not all the handbooks that give reliable constants for columns do the same for beams, nor do all those which give reliable constants for beams do the same for columns.

Until within the past five or six years, the building laws of the city of Boston prescribed that in the case of timber columns and timber beams the safe load to apply should be considered as one-third of the breaking load, the breaking load being calculated from such constants as are given by any good authority. The law did not prescribe any method of determining what is good authority, and hence left it to be tacitly assumed that any of the handbooks, or books of that character, which were used by reputable engineers or architects, might be considered as good authority. In accordance with these directions, what a man would call the breaking load of a given yellow pine beam would depend upon which handbook he happened to get his constants from.

Let us suppose that he took as his authority Hatfield's experiments on yellow pine beams, about 2 inches square and 5 feet long, and used the average of his results. In this case, he would find for extreme fibre stress, when the beam was just on the point of breaking, 15,000 pounds per square inch. Applying to this the factor of safety 3, as required by law, he would find the safe load by allowing an extreme fibre stress of 5,000 pounds per square inch, whereas modern experiment shows that, for beams of practical size, it is liable to be on the verge of breaking when the extreme fibre stress reaches 5,000 pounds per square inch.

Indeed, it is only within the last twenty years that much activity has been displayed in testing the strength of pieces of practical size, and that a flood of light has been thrown on the question as to what are not reliable constants to use in practice. In the case of most of the constants given for iron and steel, the greater part of them have

generally been nearer to the truth than in the case of timber, but there has been a very considerable lack of accurate information on the subject.

The foregoing shows that the engineer who has to perform responsible work must not trust to guesswork, but must know the principles by means of which to determine the stresses in all parts of the machine or structure, and make his calculations in accordance with these principles. He should know the character of the experiments from which are deduced the constants he proposes to use, and he should also know enough about the tests to have an opinion as to whether they were made under such conditions as to render them applicable to the work he has in hand.

Besides this, he must see, by careful inspection and tests, that the materials used are up to standard in quality. He must draw up such specifications as will secure suitable material, and then he must apply the necessary tests to determine whether it fulfils the specifications.

In order to do this properly he must, of course, know what tests structural material of suitable quality can be reasonably expected to fulfil, and what kinds of tests are necessary in order to be able to determine whether the material possesses the good qualities desired, and whether it is free from defects.

In order to know what conditions to insist upon as to tensile strength, ductility, capability of bending, etc., he must become familiar with the behavior of the materials under stress and strain, and hence he needs to make a careful study of the experiments that have been performed especially those made under such conditions as occur in practice.

In addition to this he must know what constitutes good workmanship, and he must take the precautions necessary to secure it. Unless these details are faithfully attended to, the result will not be what it should, even though his calculation of the stresses may have been all right, and his constants correct for good materials and workmanship.

In view of what I have said, one might be inclined to ask why disasters are not of more frequent occurrence, and

why our structures and machines generally are as safe as they are.

First of all, we may observe that, once in a while, some disaster happens which cannot be prevented from attracting public attention; such as the breakage of the Bussey bridge, or the bursting of the Amoskeag fly-wheel; but, frequently when breakages happen it is not considered by the management to be conducive to their best interests to publish an account of them.

Then there are cases where prospective failure makes itself evident beforehand; in other words, the piece gives warning of structural weakness, and, before an accident happens, it is either replaced by a stronger one or else it is reinforced in some way. Naturally, such cases as these are not published and are known to but a few; for the management would not consider it to be to the advantage of their firm to have the report spread among their employes or the outside public that the structural weakness existed. Cases of this kind have come to my notice.

Again, there are other cases where the structure or machine is not on the verge of collapse, but where the margin of safety is less than good engineering requires, and where the structural weakness shows itself in a lack of stiffness, and consequently in poor work, in the case of a machine; or in vibration or yielding in the case of a structure, as a building, or a bridge.

We must remember that the strength of a structure is the strength of its weakest part, and that adding to the strength of other parts is only a waste of material; also that adding material where it does not increase the strength is also a waste of material; so that a design which does not properly consider the necessary strength and stiffness of all the parts is not merely unsafe but is also uneconomical, and results in a waste of money.

Enough has been said to show the importance to the engineer of a thorough knowledge of the strength of materials whenever it comes into play in the design and construction of either structures or machines, and it only remains to show that these are matters that the engineer

has to consider and act upon at every turn, whether he is what is commonly called a civil engineer, a mechanical engineer, a mining engineer, a metallurgical engineer or a chemical engineer. To be convinced of this, we need only consider the character of some of the duties that devolve upon the engineer, in the different kinds of works which were described in the first three lectures.

Referring next to some other matters in connection with applied mechanics, I must emphasize the importance of taking the greatest care that when the young man is studying the action of the stresses in a beam bearing a transverse load, he should understand what are the assumptions, upon which the theory is based, and also all parts of the theory. Otherwise, he is liable to be led into all sorts of erroneous conclusions. As an illustration, I may say that in my laboratory of applied mechanics, where, of course, the students are required to perform a variety of tests of the strength and stiffness of iron, steel, wood, cement, etc., we are constantly testing the strength of full-size timber beams. Every once in a while one will break by shearing along the neutral axis or center of the depth, instead of tearing at the bottom or crushing at the top. I remember, on a certain occasion, when I called attention to this fact, that a gentleman proceeded to argue from it that there was a shearing force acting in the case of a beam which the common theory of beams did not take into account. Evidently to him the common theory of beams was only the set of formulæ most commonly recorded in the books, for he apparently was not aware that it does include a consideration of the shearing stresses.

Another illustration might be taken in the fact that the ordinary formulæ for the deflections of beams are deduced from an approximate equation, where one term has been neglected, which is small in all ordinary cases of beams in structures. By using this approximate equation in a case where the neglected term was very large, some one made out an imagined mathematical demonstration that an unbalanced rotating body going at a high speed pounds towards the light instead of the heavy side, a result manifestly absurd.

Again, if the student clearly understands all the assumptions made in deducing the formulæ, he will understand that the Gordon formula for columns is not demonstrated, depending as it does on assumptions that cannot be proved; and he will be in a more judicial frame of mind in trying to determine how to make use of the experimental knowledge on the subject that we possess up to date. Next, in regard to the theory of elasticity; this is necessary in considering certain cases of complicated stresses, and while we use it now to some extent, as in determining the strength of flat plates and of shafting, it will, I do not doubt, come more into use when we get more light experimentally on some matters connected with it. I need say nothing upon the importance of having a knowledge of the principles of friction and lubrication, and of the experimental knowledge on the subject up to date, beyond calling to your notice that the change from a poor to a good lubricant may often make a decided difference in the size of the dividends received by the stockholders of a large concern.

The next course to receive our attention is that of Thermodynamics and Steam Engineering. It might be assumed by some that this was peculiarly the province of the so-called mechanical engineer; but if you will consider again the account of the different works of which the first three lectures treated, you will realize that, in every work of any magnitude, power is needed, and in almost all cases the power used is steam. The exceptions are those cases where the works are favorably situated for the use of water-power, and even then steam is almost always used in addition; and perhaps I ought to make another exception in the case of sailing vessels, where the wind is used. Other sources of power, or water or wind in cases other than those mentioned, are only employed for small amounts of power.

Without power all the works would have to shut down; the bridge works could not build bridges, the machine shop or manufactory or mill would have to stop, the mine could not be operated, the rolling mill could not run, the dynamos and electric motors would be idle, the paper mill, the

sugar refinery, etc., would have to discontinue operations. Moreover, the expenses for power in any large concern form a very large item; they include the first cost of machinery, of necessary buildings, of coal bunkers, etc., the expenses of maintenance, including coal, water and attendance, and the expenses for repairs. It behooves the engineer, therefore, to try to realize the greatest possible economy. One of the largest items of expense, after the plant is once in operation, is coal, and any method by which he can save coal will increase the profits of the concern.

In order to accomplish this, the engineer must understand the principles of steam engineering, and the larger the works with which he is connected, and hence, the greater the quantity of money involved, the more important is it that he should have all the light possible, both from theory and from experiment, that will aid him in determining how his engines should be designed and built, how his boilers should be designed and built, what degree of efficiency he has reason to expect with any given arrangement which he may propose to adopt. Hence, it is plain that our prospective engineer needs a thorough course in steam engineering, of which thermodynamics is merely the theoretical part; and he needs this, whatever be the kind of engineering works he may expect to be connected with, if they are to be of considerable magnitude. In deciding upon the question as to how such a course should be laid out, we shall assume that he is already familiar with valve gears, and with the rest of the mechanism of the steam engine; also assume that he has had a course on heat in his physics, and that, in this course, he has been taught the subjects of thermometry, calorimetry, and the laws of the transference of heat.

He should be taught the nature and construction of the steam engine indicator; how it is to be used; how the indicator card is taken, and what it means, and he should acquire some familiarity with interpreting the characteristic and also some of the peculiar features of indicator cards; and then he should be made familiar with the general characteristics, *i. e.*, outward characteristics, of the different types of steam engines.

Next, he should receive a thorough drill in the principles of thermodynamics. What is thermodynamics, and what kind of a course should our prospective engineer have in the subject? Thermo-dynamics is simply the mechanical theory of heat, or, in other words, the science of heat with special reference to producing motion and power.

The subject was originally developed from the standpoint of the mathematical physicist, and we have a number of treatises written from this point of view, such as that of Clausius and others. Besides the fundamental principles of the science, they take up elaborate discussions of the nature of heat, and also a large mass of applications and developments in the direction, and from the point of view, of pure science, rather than in the direction of what we need to use in the consideration and the study of the action of the steam engine, or of other heat engines, as the gas engine, the hot air engine, etc.

Instead of this, in the course to be given to our prospective engineer, we should include a thorough treatment of the fundamental principles of the subject, a study of the laws of thermo-dynamics, Carnot's function, and the whole set of fundamental equations, and their interpretations. Then should come the applications of these fundamental principles to the gases and vapors used in practice for producing power, especially steam, and also gas and air. Then a study of the experiments that have been made, and the results of the experiments on the properties of vapors and gases; the experimental determinations of the mechanical equivalent of heat; the tables of the properties of saturated steam, as pressure, temperature, density, specific heat, latent heat, entropy, etc.; also the same for other vapors. Then a study of the laws governing the flow of fluids, both gases and vapors, through orifices and in pipes, including a consideration of the resistances and a study of the steam injector.

Then the student is prepared for a study of the behavior of steam in the cylinder of a steam engine. At this point he should be taught the modern methods of analyzing and separating the various actions of the steam

that passes through the engine, and of giving to each its proper consideration; as, for example, the heat used up in work, that used up in cylinder condensation, that used up in condensation in the jackets, if there are any, the heat rejected by the engine, radiation; also the methods of studying the effects of superheated steam, etc.; all these for both single and multiple expansion engines, and, in the cases of the latter, the effects of different sizes and arrangements of receivers, the methods of proportioning the cylinders, etc.

Next, he should learn what are the requirements for a proper engine test, both when it is made for ordinary commercial purposes, and also when it is to be made in a thoroughly complete and scientific manner for the purpose of obtaining definite knowledge as to how to produce the best and most economical results by means of a steam engine.

The day when the taking of a few indicator cards from an engine, or the making of tests in which scientific principles and scientific accuracy are neglected, and claiming that such tests can furnish information as to what the real effects of different arrangements are, is rapidly passing away, the advocates of such a course confounding themselves and each other by reaching too many contradictory conclusions by their tests.

Now, from the experimental point of view, the student should have presented to him, in a carefully systematized form, an account of such experiments as have been made, with such a degree of accuracy and such regard for scientific principles as to render them worthy of study. Of course, there will be a number of tests in this list which are not up to the scientific standards of to-day; but such a study will make the student familiar with what is the extent of our knowledge of the subject up to date, and he will be all the better able to make this study effective, by being relieved of the necessity of reading accounts of a lot of worthless tests for the sake of finding out those that are worth considering.

Then he should have a good course on steam boilers,

including the construction and action of the various types in use; on the laws controlling the combustion of fuel, and the evaporation of water; on questions of heating surface, grate area, tube section, horse-power, capacity, evaporative efficiency, evaporation from and at  $212^{\circ}$ , priming or superheating, draught, quantity of air required for combustion, temperature of flue gases, size of chimney, methods of feeding, methods of determining quality of the steam; and on boiler accessories, such as gauges, water glasses, grates, stokers, feed pumps, injectors, feed water heaters, economizers, damper regulators, etc. This instruction should embrace also the requirements for a reliable and accurate evaporative test; what are the possible maximum evaporative efficiencies, and what are usual evaporative efficiencies attainable under ordinary conditions.

He should also study the more recent applications of thermo-dynamics, such as air compressors, gas engines and refrigerating machines. In these cases a lack of familiarity with the laws of thermo-dynamics on the part of the makers is very likely to make itself apparent to the user through the medium of his pocket-book, and in no case will this be more likely to be true than in the case of the refrigerating machine, either for cold storage or for the making of artificial ice, and those who are engaged in this business are very rapidly realizing this fact.

Now, when the student has finished the work referred to on the steam engine indicator, and has acquired the fundamental principles of thermodynamics, and is studying the action of the steam in an engine, it is a proper time for him to begin work in the laboratory, by making steam engine tests, alternating his duties at each successive test until he has been drilled in performing all the different parts of the work, and in making all the necessary calculations. For this purpose a small engine is, of course, better than none, but it is much better for the education of the student if his work can be done upon an engine sufficiently large to work with an economy comparable with that found in such engines as are used in large and well-designed modern plants. Such tests made by the student himself, under the

direction and guidance of the instructor, will leave a lasting impression upon his mind, and will convey information which he cannot acquire as well in any other way. Hence, it is far better to use a triple, or at least a compound engine, of sufficient size to secure a steam consumption of about fourteen or fifteen pounds of water per horse-power per hour, than to use a small single engine, where the steam consumption per horse-power per hour is as high as thirty, forty or more pounds. In making the tests no loose work should be allowed, but the student should be required to perform all the work with the greatest accuracy possible, and this accuracy should be such as to render the test thoroughly reliable from a scientific standpoint. This can be accomplished provided the instructor exercises the necessary supervision over the work.

Later in the course the student should make accurate and carefully conducted boiler tests on some large boilers. By these methods, he will be made to appreciate better the work which he is doing in the class-room and will see that it finds its application in just such work as an engineer has to do in the course of his profession. Of course, he should have to perform other sorts of experimental work with steam in the laboratory besides engine and boiler tests, but of these will be referred to later.

The whole idea of such a course as I have outlined is, as you will see, to give the student a thorough drill in the fundamental principles of the subject, and then to teach him how these principles apply to the work of the engineer, by means of both class-room and laboratory work, the deductions and developments from the fundamental principles being made in the direction of engineering work, instead of in the direction of pure science; and then, by means of this work, and also by showing him where we stand to-day in regard to the matter of reliable experimental results, to equip him as fully as possible to appreciate and to take part in the best and most scientific engineering work of the present times, and thus to be ready in the future, ever to take advantage of, and to take his part in developing, whatever progress the future may have in store for us.

Another fundamental subject is hydraulics. Our prospective engineer should understand the principles of hydrostatics and hydrodynamics; in other words, the laws governing the pressure of water, and the flow of water, whether in pipes, in open channels, through orifices or over weirs. He should also be familiar with the character and the results of such experiments as have been made upon these subjects, and should know how to conduct such experimental work.

Whatever may be the special line of engineering in which he is engaged, he is liable to have to establish a water supply, with all the necessary works, such as reservoirs, pumping engines, piping, etc.; or to build a system of sewerage, or he may find his manufactory so situated that it is advisable to take advantage of a water-power, and to build all the necessary works, such as dams, canals, locks, sluice-ways, etc. He may have to establish river or harbor works, or, even if not these, he may have to build a wharf, a quay, or even a dock, if his works are on the water's edge. Unless he is to make a specialty of hydraulic work, he cannot, in a four years' course of engineering, afford the time to make himself master of the details of all these kinds of works, but he should become familiar with the principles stated above, and then he can afterward make a special study of part or all of these subjects.

Next comes the question as to how far electricity should be accounted a fundamental subject, and consequently one to be required of all engineering students, whatever their special lines.

It is now usually customary to require them to learn some electricity in connection with general physics, and sometimes a little more; the rest being given to students of electrical engineering only.

Whether or not a considerably larger amount should be put in the list of fundamental studies, will depend upon how far and how intimately electrical appliances come to associate themselves with the every-day work of the engineer, whatever his specialty. The probabilities are, it seems to me, that it will not be many years before we shall

have to insert a much larger amount of electricity than we now do in our list of fundamental studies.

The subjects thus far enumerated are fundamental, and are necessary for our prospective engineer, whatever be the special line of engineering to which he is to devote himself. He cannot afford to do without any one of them.

In laying out, therefore, any engineering course, of whatever name, whether civil, mechanical, mining, metallurgical, electrical, or chemical engineering, we should arrange, first of all, the time necessary to give good courses in mathematics, general physics, drawing (including descriptive geometry), mechanism, applied mechanics (including, of course, strength of materials), thermo-dynamics and steam, and the general principles of hydraulics. Moreover, thorough instruction in these should not be sacrificed to any other subjects, whether of an engineering or of a general character. In other words, the work in these subjects should be thoroughly performed, whatever else is or is not accomplished.

When this has been done, we can then, and not till then, begin to consider what other subjects should be added, and these may be classified as follows: (1) subjects of a professional nature bearing on the work of an engineer in general, whatever his specialty; (2) subjects of a professional nature, which bear directly on the special line of engineering which the course is intended to teach; (3) subjects of a non-professional character intended to broaden the field of knowledge and to impart general information; (4) subjects which fulfil partly one of these functions, and partly another.

In the first class, though respectively of very different degrees of importance, I should place (*a*) machine design, (*b*) dynamics of machinery, (*c*) metallurgy of iron, (*d*) heating and ventilation, (*e*) stereotomy, (*f*) surveying, (*g*) shop-work. How many, and which of these subjects can be added will depend upon circumstances.

Reviewing in detail the kind, of course, I have in mind under each of these heads, I will make the following remarks:

(a) *Machine Design*.—This course, to be of the greatest value, should take up problems of real engineering design, and should deal especially with the details. Thus the student should be made to study each separate piece, and its connection with the other pieces, to determine the forces acting upon it, and the stresses to which the piece is subject in consequence of the action of these forces, and to design the separate details in such a manner that they shall have the requisite strength and stiffness.

Of course, it is desirable, also, to have some work done on mechanism design, where the student shall have practice in adapting mechanisms to the special objects that are to be accomplished, but it is also important that he should learn that in making any such design, he must study the strength and stiffness of each separate piece of which the machine is composed, and must be fully impressed with the facts that any one of these that is not properly designed, means a machine that is not properly constructed and may mean the total failure of the resulting mechanism.

(b) Under the term dynamics of machinery, I include such subjects as governors, fly-wheels, dynamometers, the action of the reciprocating parts of a steam engine, etc. I need only mention these topics to make plain their importance to any engineer.

Metallurgy of iron and heating and ventilation will, I think, also make plain their importance by a mere mention of their names.

Stereotomy is a species of advanced descriptive geometry, and can easily be acquired by any one who is familiar the latter subject. It bears more especially upon the work of the engineer who is to erect large buildings where stone plays an important part, or masonry bridges.

Of surveying and topographical drawing, of course, every engineer ought to have some knowledge, but the principles of surveying are easily learned by any one who has a scientific training and some skill in handling measuring instruments, and nicety of execution can only be acquired by long-continued practice, and the greater part of this practice will have to be acquired subsequently. Sur-

veying has sometimes been assumed to be the principal business of the civil engineer, and frequently a man who was merely a surveyor has called himself a civil engineer; but the progress of the world is sweeping this away, and a man who is merely a surveyor is no longer considered to be an engineer any more than a machinist is an engineer. Now, while the man who is to build roads or railroads will probably have to use surveying to such an extent that it will be necessary to give him in the school more than is given in the other engineering courses, nevertheless his practice will have to be acquired subsequently, and the instruction in those things that he cannot acquire later, or can only acquire later with a great deal of difficulty, should, on no account, be sacrificed for surveying.

When we come to the higher geodetic work, we have geodesy, and not engineering and hence it will not be considered here. Then as to shopwork, very similar remarks to those I have made in regard to surveying, will apply. It is something in which every engineer should have some practice, but which should not be given at the expense of more important engineering work. Indeed, it would be extremely desirable that this should be acquired at the manual training schools before beginning an engineering course, and whenever the manual training schools are established everywhere as a part of the public school system, so that young men who wish to take an engineering course at some engineering school can first attend the manual training school, then the engineering schools will not need to teach so much shopwork and what they do teach will be of a more advanced character.

Coming, now, to the studies of the second class, we shall find that we may divide them into two classes, the first being those requisite for such specialties as can be developed by a suitable addition of certain lines of work, but where these lines of work depend upon the previous training that has been given; and second, those where a considerable knowledge of, and hence a drill in, chemistry is necessary. Among the first I should place: (1) bridges; (2) hydraulic engineering; (3) railroad engineering, with special

reference to permanent way; (4) railroad engineering, with special reference to motive power and rolling stock; (5) marine engineering; (6) mill engineering; (7) naval architecture; (8) electrical engineering; and others as they might arise.

In the second class, on the other hand, I should place mining, metallurgical and chemical engineering, and others as they might arise.

The essential difference between these two classes is that, in the latter, a considerable knowledge of chemistry is required, and, consequently, that the student must have considerable instruction in elementary chemistry and in qualitative and quantitative analysis, before he is in condition to discuss the subjects pertaining to his special line; and hence, that for these courses, a certain amount of chemistry becomes one of the essential fundamental studies that the student cannot do without, and must be provided for at the start by assigning the necessary time for it in addition to that needed for the other fundamental studies. When suitable provision is made for this, there remains, of course, less time for other subjects than there is in the other cases.

Of course, the amount of chemistry required is a matter of degree. In some lines of mining engineering it is not great, whereas, in metallurgical works, or in chemical works, the amount is decidedly larger.

Nevertheless, the one who is laying out any of these courses must bear in mind that they are intended to fit men to do primarily the engineering work of such establishments, and that it is not necessary that they should have as much chemistry as would be required by the analytical chemist. Hence, he should begin by considering what is the minimum amount of chemistry which it will do to put in the course; put that in, and then leave the rest of the chemistry, which it might be desirable to add, to take its chances with the other professional subjects, according to their relative importance in the special line of work for which the course is laid out.

Let us assume, now, that we have fixed upon the fundamental subjects, and the time that must be given to each.

We are prepared, then, to map out the course to be pursued in the second class, or special line of studies, including whatever of the first class we deem wisest to insert in the list.

Were I to attempt to map out the details of what should be given in the case of each special engineering course in these special lines, I should need a whole course of lectures to elaborate it. I shall only say a little, therefore, about some general rules to be observed in making the selection:

(1) To drill the student in all the details of his profession, or to impart to him experience, is not possible in a school. Experience can only be gained after the school days are past, and he goes to work.

(2) To attempt to perfect him in those things that he will have to do when he first goes to work, at the expense of his later success, is a very short-sighted policy.

(3) Hence, the object to be attained should be, first, to so arrange this work that he shall have to deal with such cases as are liable to arise in the practice of his profession, as with the actual details of a bridge, of a steam engine, of a locomotive, of a mill, etc., and thus become familiar with what he is likely to meet later on; and secondly, that he shall be taught how to go to work on these problems in a scientific manner, applying the principles that he has previously learned, thus teaching him what is the relation of his scientific study to the practical problems he will meet later in life.

Next, in regard to the third class of subjects, or those intended for general information, it is desirable to insert as much as can be inserted, without sacrificing the accomplishment of the main objects of the course.

Such subjects are, mainly, linguistic and literary studies. The first, however, if confined to the modern languages, are also, to a certain extent, professional; for, without modern languages, some of our most valuable engineering literature is closed to the student.

Having thus marked out the character and the scope of the studies that should enter into an engineering course of one or of another kind, it remains for me to speak of two subjects, viz.: (1) The graduation thesis, and (2) the extent

to which laboratory practice in the engineering laboratories should be introduced into the courses.

First, as to the graduation thesis. It has always been the custom for the engineering schools to require of the students, before they are graduated, a thesis. The special feature required of a thesis should be that it shall involve an element of original investigation, and its chief object is to teach the student how to make, and to give him practice in making, original investigation on his own account. He should be made to feel that the problem is his own to solve. He should be encouraged to propose his own plans for the solution, and to submit them to some one member of the corps of instruction, who should aid him when he needs aid, and exercise so close a supervision over his work, that he should be made to do it correctly.

If this supervision is properly maintained, a large amount of investigation can be accomplished in connection with the thesis work.

In giving the instruction I have outlined above, it should not be merely class-room instruction, but also laboratory work, partly to emphasize and illustrate the work of the class-room, partly to drill the student in performing carefully and accurately such experimental engineering work as he is liable to be called upon to perform in the practice of his profession, and partly to teach him experimental investigation.

The student will have, of course, in addition to this, laboratory work in his special line, as in the mining laboratory, electrical laboratory, industrial chemistry, laboratory, etc., besides, of course, work in the chemical and physical laboratories.

I have previously called attention to the process of gradual development which has resulted in the extensive introduction of laboratory practice of a variety of kinds into technical instruction, and therefore to the evolution of the engineering laboratories.

As to the organization of such laboratories, the principal objects to be accomplished by them are three, to wit:

(1) To give the students practice in such experimental work as an engineer is constantly liable to be called upon to perform in the practice of his profession, as tests of the strength of materials, evaporative tests of steam boilers, steam engine tests, calorimetric tests, valve setting, etc.; and to teach him to carry on his work with accuracy, and to take all proper precautions to avoid error.

(2) To give the student opportunity of carrying on original investigation in the engineering branches, such as investigations in strength of materials, in steam engineering, etc.

(3) Another important function of such laboratories, which is entirely consistent with the other two, is that of taking up and carrying on systematic investigations of engineering problems, and this can be done in a laboratory, whereas it is only with very great difficulty that it can be done in a machine shop or a manufacturing establishment.

By publishing these results from time to time the laboratory will serve to add gradually to the common stock of knowledge.

I recognize very fully the incapacity of the student, as a rule, to originate and carry on research without aid from his teachers; but when this aid is given, and the necessary supervision is exercised, a large amount of research can be accomplished in such laboratories.

Original researches should also be carried on by the students in connection with their graduating theses; some of them are, of course, better able to do this kind of work than others, but all should be required to undertake original research, and a careful supervision should be exercised by some one of the instructing force, who should see to it that whatever is done should be properly done, so that the results, as far as they go, whether extensive or not, may be of real value.

Inasmuch as the number of important investigations which it is possible to take up and carry out is so very large that only a few can be undertaken in any one laboratory, and, therefore, while there are certain pieces of apparatus

of so typical and general a character that all engineering laboratories need them, and should be provided with the best that their means will admit of, as for instance, testing machines and steam engines—the remainder of the apparatus may vary very considerably in equally well-equipped engineering laboratories.

Instead, therefore, of laying down general rules for the equipment and conduct of such laboratories, it seems to me that I shall be better able to convey my ideas by describing to you the equipment of the engineering laboratories of the Massachusetts Institute of Technology, and the way in which they are conducted.

The first attempt at establishing engineering laboratories at the Institute was made in the school year 1873-74, when one was equipped with the following apparatus, viz.:

(a) Two horizontal tubular boilers, each 4 feet in diameter and 12 feet long, containing fifty 3-inch tubes; (b) one small vertical tubular boiler, 3 feet in diameter, and 7 feet high, containing fifty 2-inch tubes; (c) a cast-iron superheater; (d) an 8-inch by 24-inch Harris-Corliss engine, with a brake on the fly-wheel; (e) a combined surface condenser and calorimeter with the necessary tanks and scales; (f) also a variety of accessory apparatus, as indicators, gauges, etc. From this laboratory there emanated an investigation into some special problems on cylinder condensation made for Mr. George B. Dixwell.

From these small beginnings, partly through gradual growth, and partly through considerable changes and improvements made all at one time, have arisen our present engineering laboratories, situated in the Engineering Building, and occupying two floors, 50 x 150 feet each.

The equipment of the Laboratory of Applied Mechanics *i. e.*, the laboratory for testing the strength of materials, embraces the following apparatus:

(1) A testing machine of 300,000 pounds capacity, made by William Sellers & Company, Incorporated, under the patents of Albert H. Emery, the maker of the Government testing machine of 800,000 pounds capacity at Watertown Arsenal.

This machine has recently been added to the equipment of the laboratory, and it is to be observed that this style of testing machine is the most delicate and accurate in the world. Moreover, the amount of investigation in the line of strength of materials of such a character as to be of positive value to the engineer, which has been made by means of the Government machine at Watertown, is far greater than that which has been accomplished by means of any other testing machine in the world.

It is provided with suitable holders and measuring apparatus to adapt it to specimens of different shapes.

(2) An Olsen testing machine of 50,000 pounds capacity for determining tensile strength, elasticity and compressive strength.

This machine is furnished with compression platforms, which distribute the pressure evenly over the specimen.

(3) A testing machine of 100,000 pounds capacity for determining the transverse strength and stiffness of beams up to twenty-five feet in length. By means of this machine tests are also made on the strength of framing joints used in practice, and on the strength of the riveted joints of plate girders, as well as on other specimens subjected to transverse stress.

(4) A testing machine of 18,000 pounds capacity for determining the transverse strength and stiffness of beams up to fifteen feet in length.

(5) A machine of 144,000-inch pounds capacity for testing the torsional strength and stiffness of shafting up to twenty-one feet in length, provided with apparatus for measuring the angle of twist to four seconds of arc.

(6) A testing machine of 25,000 pounds capacity for determining the strength of ropes or wire, where the clear length of the specimen can be made as great as ten feet. By means of this machine tests are made upon both long and short splices, and on a variety of hitches and holders.

(7) A machine for testing the tensile strength of cements and mortars, where the clips have been specially designed in such a way as to secure an evenly distributed pull on the specimen. In connection with this machine is a complete

outfit of nicely-constructed moulds for making the briquettes or specimens, and also all other necessary apparatus as sieves, tanks, etc.

(8) A machine for determining the strength and elasticity of long specimens of wire.

(9) A machine for determining the strength and elasticity of cloth.

(10) A machine for determining the effect of repeated stresses on the strength and elasticity of iron and steel.

(11) A machine for determining the deflection of parallel rods when running under different conditions.

(12) A quantity of measuring and other apparatus for determining stretch, deflection and twist.

The students who take the subject of applied mechanics in their senior year are required to learn how to use this apparatus, and the method of making the different kinds of tests, thus learning how tests should be made, and also acquiring a familiarity with the appearance and behavior of materials when subjected to stresses such as occur in practice.

Thus, in the school year each student makes the following tests in the laboratory:

(1) A test to determine the modulus of elasticity, the limit of elasticity, and tensile strength of a cast iron or wrought-iron or steel rod or bar, or the transverse strength of a coupling.

(2) A test of the deflections and of the transverse strength of a full-size iron or steel I beam, or of a wooden beam subjected to transverse load.

(3) A test to determine the modulus of elasticity and the tensile strength of various kinds of wire.

(4) A test to determine the shearing modulus of elasticity and the torsional strength of a shaft.

(5) Tests of the tensile strength of hydraulic cement.

(6) Tests of the compressive strength of hydraulic cement.

(7) Tests of the strength of rope, and the loss of efficiency due to different hitches and knots.

(8) Besides the above the students make a variety of tests of large pieces on the Emery testing machine; some-

times compression tests of full size columns, or of small blocks, or of columns with bolsters, etc., and sometimes tensile tests of pieces of varying shapes and sizes.

The hydraulic laboratory contains:

(1) A closed tank, 5 feet in diameter and 27 feet high, connected with a 10-inch stand-pipe over 70 feet high, so arranged that a constant head may be kept at any desired level.

(2) Apparatus in connection with the tank and stand-pipe, for making experiments on the flow of water through orifices and mouth-pieces, over weirs and in pipes, under different heads and conditions, and on the losses of head occurring under different circumstances.

(3) A system of pipes, connected both with the main pipe and with the pumps, is fitted for the insertion of diaphragms, branches and other apparatus for studying loss of head and the laws of discharge.

(4) An attachment to the main tank, containing a Pitot tube for studying the laws of velocity in jets, and adjustable points for the measurement of the cross-section of jets.

(5) A cylindrical steel measuring tank of 280 cubic feet capacity.

(6) A six-inch Swain turbine, so arranged that it can be run under different heads, and that measurements can be made of the power exerted, of the efficiency, etc., under different gates.

(7) A 48-inch Pelton water motor, similarly arranged.

(8) A Venturi meter and numerous hose nozzles for measuring water.

(9) A weir of adjustable width up to four feet.

(10) A hydraulic ram with a two and one-half inch drive pipe.

The steam laboratory contains:

(1) A triple-expansion engine, with cylinders of 9 inches 16 inches, and 24 inches diameter, respectively, by 30 inches stroke, arranged in such a way as to be run single, compound or triple, as desired for the purposes of experiment. It is of the Corliss type, and has a capacity of about 150 horse-power when running triple, with an initial pressure of

150 pounds in the high-pressure cylinder. To it is connected a surface condenser, and the other apparatus needed to adapt it to the purposes of accurate experiment.

The ends and barrels of the cylinders are separately jacketed, so that steam can be let into either or both. The receivers are also jacketed so that they can be used either with steam in the jackets or not. The cut-off on all three cylinders can be thrown into connection with the governor, or any of them can be disconnected from the governor and adjusted by hand at a fixed point. Cans are provided for catching the drip from each jacket, and these cans are provided with water-glasses so that we can determine its quantity.

The engine is thus fitted to carry on series of experiments under different conditions, and by its use we can obtain results comparable with the results that are actually realized on large marine and stationary engines. The water consumption per horse-power per hour varies with the different conditions under which the engine is run, but we have found it under some conditions as low as 13.7 pounds.

A very considerable amount of investigation has been carried on already, and valuable results have been obtained.

(2) A Harris-Corliss engine, with cylinder 8 inches diameter by 24 inches stroke, with a capacity of about 16 horse-power, with an initial pressure of 75 pounds. This engine is also connected with a surface condenser and a tank on scales to weigh the condensed steam, and, of course, it can be used to make engine tests; but inasmuch as it is a small engine, it is not economical, using from 30 to 40 pounds of water per horse-power per hour; and, now that we have the triple expansion engine, we use the Harris-Corliss machine mainly for valve-setting. Moreover, this Harris-Corliss engine is the original one that was put in the laboratory when it was first founded, in 1873, by means of which the investigations were made for Mr. Dixwell.

There is also another eight-horse-power engine used for valve-setting, etc.

(3) Of surface condensers there are four in all: (a) the one connected with the triple-expansion engine, and which

is also specially arranged for experimental purposes in such a way that the condensing water can be made to pass once, twice or three times the length of the condenser while performing its functions; (b) a smaller surface condenser attached to the Harris-Corliss engine, and (c) and (d) two other surface condensers, used in various experiments.

(4) A mercurial pressure column which extends to 160 pounds pressure, by means of which our gauges are tested. There is also a mercurial vacuum column.

(5) A dynamic steam engine indicator tester.

(6) Several pieces of apparatus for determining the quantity of steam issuing from a given orifice, or through a short tube, under a given difference of pressure.

(7) Apparatus for testing steam injectors.

(8) A number of steam pumps, the largest one being a duplex pump 16, 10½ by 12 inches.

(9) A number and variety of calorimeters.

(10) A large supply of indicators, planimeters, gauges, thermometers, anemometers and other accessory apparatus.

(11) There are in the different buildings two 208-horse-power sectional boilers, two 100-horse-power, and one eighty-horse-power horizontal tubular boilers, and another sixty-horse-power horizontal tubular boiler at the shops, and these are used for making boiler tests; all the fourth year students of mechanical, electrical, chemical engineering and naval architecture, having to take part in these tests.

It is believed that the students can best learn to make boiler tests by making them on large boilers producing a considerable quantity of steam.

Besides all the above, the engineering laboratories are provided with several friction brakes of different capacities; with machinery for determining the tension required in a belt to enable it to carry a given amount of power, at a given speed, with no more than a given amount of slip; with a machine for testing the transmission of power by ropes; with a number of transmission dynamometers; with a four-horse-power gas engine; with a complete set of Westinghouse air-brake apparatus, including the parts belonging to the car and to the locomotive; with the pump and engineer's

valve of the New York air-brake ; with a measuring tank for large quantities of water, this tank being provided with a number of orifices in the bottom, and a water glass on the side ; with a number of water meters, and of weirs of different sizes, for measuring water ; with a locomotive link model ; with a centrifugal pump, a gang pump and a rotary pump ; with a hot-air engine ; with a pulsometer pump ; with an experimental governor ; with an oil-testing machine ; with a number of water motors ; with an ejector ; and with cotton machinery as follows : two cards, a drawing frame, a speeder, a fly frame, a ring frame and a mule, as well as accessory apparatus. As to the work required of the students of mechanical, electrical and chemical engineering, I will say that in the second term of their junior year they are required to make, under careful supervision, engine tests on the triple engine. In the course of the senior year the list of tests made by each student is approximately as follows, viz.:

Tests of the transmission of power by belting ; test of the performance of a surface condenser ; test of a direct-acting steam pump ; test of the flow of steam ; valve setting (plain slide valve) ; test of a pulsometer ; test of a plunger pump ; calibration of orifices for the flow of water ; determination of the clearance of an engine ; use of the different dynamometers ; valve setting (double valve) ; testing gauges by means of the mercury column ; test of some of the boilers ; test of the steam injector ; test of steam ejectors ; use of the different kinds of calorimeters ; test of a Swain turbine ; measurement of the flow of water by means of orifices and weirs ; test of water motors ; test of a hot-air engine ; valve setting (Harris-Corliss engine) ; analysis of chimney gas ; test of a battery of boilers application of Hirn's analysis to the triple-expansion engine in the laboratory ; test of the efficiency of a Weston differential pulley block ; test of the efficiency of jack screws (each test is performed by a squad of from two to five students, and the results are then worked up and handed in within two or three days by each member of the squad) ; test on experimental governor ; tests on the indicator tester ; tests on

the gas engine; tests of water meters; calibration of hose nozzles, etc.

The tests are all made under such supervision as will insure accurate work, and reliable results.

Then each student is required to make all the calculations for every test in which he takes part, and to hand them in within a week.

These reports are examined by competent instructors who make all the calculations independently before examining those of the students.

Then each student is furnished with the results of all the tests in which he takes part, and, moreover, the results of the investigations made in the course of the regular laboratory work of the engineering laboratories is regularly published in the *Technology Quarterly*.

The above is a description of the equipment of, and the work done in, these laboratories at the Massachusetts Institute of Technology. It is plain that some of the most common work of the engineer in practice will be to make tests of steam engines and of steam boilers, to make tests of power and to determine quantities of water either in hydraulic work or in work on steam.

Now, the young engineer should be drilled in doing this work accurately and well, and should understand what constitutes good work; more especially is this of importance because there are so many so-called engineers who make tests carelessly and publish results which have been obtained from tests erroneously made. Too often they do not give a detailed description of how they made their tests. Before one can judge of the credibility of the results of a test, he needs to know how the test was made.

The student should be taught to do all that he does, well and thoroughly. It will be easy enough to teach him to do rough work when it is required if he knows how to do accurate work, but if he is accustomed to do rough work it will be very difficult to make him do accurate work.





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